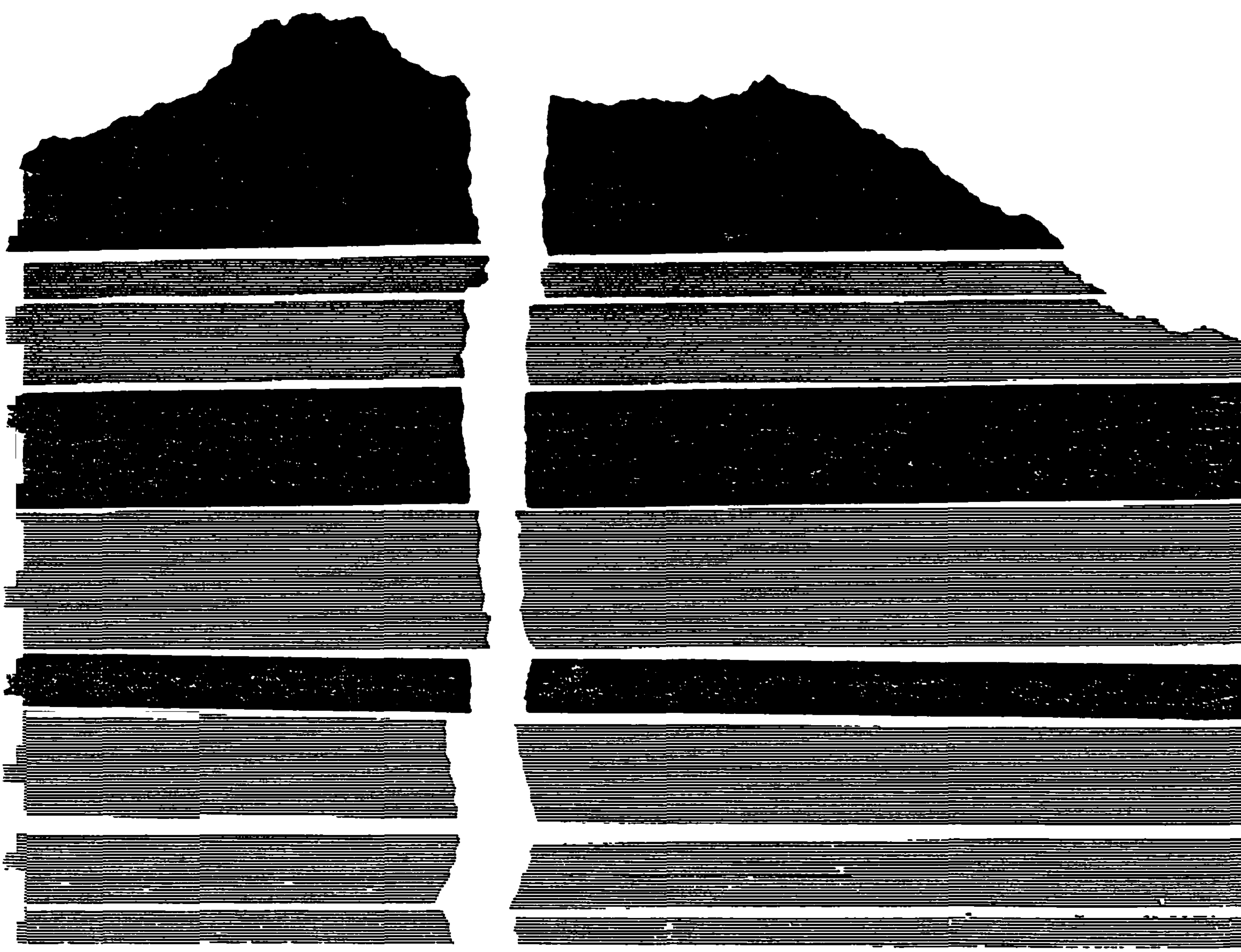
IWWA/EPA Series

Methods for Determining the Location of Abandoned Wells

Linda Aller



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METHODS FOR DETERMINING THE LOCATION OF ABANDONED WELLS

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in cooperation with
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DISCLAIMER

Although the research described in this report has been funded wholly or in part by the United States Environmental Protection Agency through grant CR-809353 to East Central Oklahoma State University, it has not been subjected to the agency's peer and policy review and therefore does not necessarily reflect the views of the agency and no official endorsement should be inferred, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated zone and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective, and provide adequate environmental protection for the American public.

Clinton W. Hall
Director
Robert S. Kerr Environmental
Research Laboratory

PREFACE

Methods for Determining the Location of Abandoned Wells has been developed under the guidance of East Central University, in conjunction with the U. S. Environmental Protection Agency, for use by all of those involved in efforts to locate abandoned wells. Techniques described are those which are currently in use and methods which may be of future significance.

For those concerned with protecting ground water, this document may be helpful as a ready summary of ways to locate penetrations in the earth which may be or may no longer be physically evident at the surface. Finally, this manual partially fulfills a mandate contained in the Safe Drinking Water Act (P.L. 93-523) requiring the Administrator of the Environmental Protection Agency to "...carry out a study of methods of underground injection which do not result in the degradation of underground drinking water sources."

ABSTRACT

Improperly plugged or unplugged abandoned wells which penetrate an injection formation may provide a conduit for migration of injected fluids into fresh water formations. To help minimize this serious environmental threat, all abandoned wells within an area of review around a proposed injection well should be located and their condition assessed.

A search for abandoned wells may have three different objectives: 1) to provide an overview of the presence or absence of abandoned wells within an area, 2) to determine the status of a particular well and establish the potential impact of that well, and 3) to actually field locate the abandoned well. The scope of a search may encompass all or any combination of these objectives before the search is completed.

To date, few methods have been successfully used to search for abandoned wells. This document contains a discussion of the application of methods which historically have been used to locate abandoned wells including record searching, talking with residents, using visual and logical clues to look for the well, walking over the area with a metal detector or magnetometer and excavation. Additionally, this document addresses technologies which may not have been specifically developed for locating abandoned wells, but which may have future application. These technologies include geophysical methods such as electrical resistivity, electromagnetic conductivity and ground penetrating radar, remote sensing techniques such as black and white aerial photographs, color photographs, color infrared imagery and thermal imagery, and indirect methods such as water-level measurements or actual injection. Although this document has been specifically designed to outline methods for the location of abandoned oil and gas wells, the techniques described herein may also be applicable to locating abandoned water wells, mineral exploration boreholes, engineering borings and similar subsurface excavations.

This report was submitted in partial fulfillment of Contract No. CR-809353 by the National Water Well Association under the sponsorship of the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma and in cooperation with East Central University Environmental Research Institute, Ada, Oklahoma. This report covers a period from December, 1981, to September, 1983, and work was completed as of September, 1983.

CONTENTS

Disclaimer. ii
Foreword iii
Preface iv
Abstract. v
Figures viii
Tables xi
Acknowledgements xii

1. Introduction 1
2. Conclusions 8
3. Recommendations 13

Part I: Methods Historically Used to Locate Abandoned Wells

4. Search of Records 14
5. Conversation with Local Residents 29
6. Visual/Logical 32
7. Aerial Photographic Interpretation 41
8. Metal Detectors 52
9. Magnetometers 59
10. Combustible Gas Indicators 71
11. Excavation 77

Part II: Methods Which Have Not Historically Been Used To Locate Abandoned Wells

12. Electrical Resistivity 79
13. Electromagnetic Conductivity 88
14. Ground Penetrating Radar 94
15. Remote Sensing 100
16. Water Level Measurement in Surrounding Wells 107
17. Injection 113

References 118
Appendices

A. Regulations, requirements and methods used by state government agencies to locate abandoned wells 124
B. State depositories of oil and gas well logs 126

FIGURES

Number		Page
1	Diagram showing how fluid migration from an injection zone through an abandoned well and into a fresh-water zone may occur	4
2	Part of a county map showing the location of oil and gas wells	16
3	Part of a county tax map showing wells drilled around 1885	17
4	Part of a township map illustrating typical platted information for more recent wells	18
5	American Petroleum Institute standard map symbols	19
6	Detailed location map clearly showing the location of the well.	20
7	Location map showing an example of a well location which is not clearly defined	21
8	Well location map which leaves the location to the imagination of the interpreter	23
9	Plan and elevation of an 82-foot standard cable tool rig	33
10	Plan and elevation of a 100-foot rotary rig	34
11	Steam-driven rotary rig of the 1930's showing surface equipment and boiler-plant layout	37
12	Surficial evidence of supporting structures around abandoned wells, Cleveland County, Oklahoma	38
13	Parts of two flight strips of aerial photographs superimposed to show characteristic overlaps	42
14	Position of pocket stereoscope relative to two photographs of a stereo pair	42
15	Aerial photography summary record from National Cartographic Information Center	44

FIGURES (Continued)

Number		Page
16	Explanation of symbols and codes on aerial photography summary. .	45
17	Aerial photograph showing derricks, Osage County, Oklahoma, 1937	49
18	Aerial photograph showing central powerhouse, rod lines to the powerhouse and brine pits, Osage County, Oklahoma, 1937	50
19	Metal detectors	54
20	Metallic evidence uncovered in the vicinity of abandoned well, Appalachian area and Midcontinent area	56
21	Location of metallic objects excavated from the area around abandoned well, Appalachian area	57
22	Diagram showing magnetic field surrounding well casing and metal object	61
23	Different types of portable magnetometers	63
24	Comparison of observed and theoretical anomaly produced by a 4,609 foot vertical string of casing	64
25	Different effects of pipeline on the shape of a curve plotted from readings obtained from a magnetometer.	65
26	Airborne magnetometer mounted in an airplane or suspended from a "bird" and contour map produced from a hypothetical aerial survey	66
27	Operation of combustible gas indicator	73
28	Graphic representation of decreases in methane concentration as search probe is moved from center of wellbore	74
29	Diagram showing basic concept of electrical resistivity measurement	80
30	Electrical resistivity survey equipment	82
31	Field operation of electrical resistivity equipment	83
32	Diagram showing basic concept of electromagnetic conductivity measurement	89

FIGURES (Continued)

Number		Page
33	Field operation of electromagnetic conductivity equipment by one and two man crews	91
34	Example profiles obtained from a ground penetrating radar survey.	95
35	Computer-produced map view of radar reflections at survey site. .	97
36	Diagram of thermal infrared scanner system	102
37	Thermal infrared image and panchromatic photograph showing Kilauea volcano, Hawaii	103
38	Diagram showing confined and unconfined aquifers	108
39	Diagram illustrating water level increases in wells surrounding an abandoned well	110
40	Diagram of the relationship between an injection well and a flowing abandoned well	114
41	Diagram of the relationship between an injection well and an abandoned well which does not flow at the surface	115

TABLES

Number		Page
1	Summary of application, advantages and disadvantages of each method which may be used to locate abandoned wells	9
2	Summary of wells and well status, within an area of review, Case History #2	26
3	Typical costs for standard aerial photography available from the U.S. government	47

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SECTION 1

INTRODUCTION

OBJECTIVES AND SCOPE

Methods for Determining the Location of Abandoned Wells has been prepared as an aid to state and federal authorities concerned with identifying the location of abandoned wells prior to authorizing the issuance of permits for Class II wells under the Underground Injection Control Program (UIC). The manual is also designed to assist industry representatives, engineers, geologists and others with the task of locating abandoned wells which may pose a potential problem to the issuance of such permits. Information contained within this publication is also applicable to identifying the location of abandoned wells for a variety of other purposes.

This manual is intended to be informative rather than prescriptive in nature. The basic objective is to provide a concise description of methods or technologies which are currently being used or which may have applicability in locating abandoned wells. The information is presented in a form that is convenient for use by regulatory agencies, private industry and others in performing their respective tasks so that injection wells may be used with a minimum potential for environmental damage.

Impetus for the development of Methods for Determining the Location of Abandoned Wells was provided by passage of Public Law 93-523 (the Safe Drinking Water Act) and the subsequent enactment of federal regulations found in 40 CFR Parts 122, 123, 124 and 146 (the UIC Program). The Safe Drinking Water Act of 1974 requires the U.S. Environmental Protection Agency (EPA) to develop minimum requirements to assist in the establishment of effective state programs to protect underground sources of drinking water from the subsurface emplacement of fluids through well injection. Additionally, the Act states that these requirements not impede the re-injection of brine or other fluids resulting from oil and natural gas production or the injection of fluids used in secondary or tertiary recovery unless drinking water sources would be endangered (Federal Register, June 24, 1980).

40 CFR Parts 122, 123, 124 and 146, (the UIC Program) were enacted under the authority of PL 93-523. 40 CFR Part 122 defines the regulatory framework of EPA-administered permit programs; 40 CFR Part 123 describes the elements of an approved state program and criteria for EPA approval of that program; 40 CFR Part 124 describes the procedures the agency will use for issuing permits under covered programs; and 40 CFR Part 126 sets forth

technical criteria and standards for the UIC (Federal Register, June 24, 1980). A discussion of some of the pertinent sections of 40 CFR Part 146 are described below.

Underground injection is defined as the subsurface emplacement of fluids through a well (146.03). For purposes of the UIC program, injection wells were classified into five categories based on the nature of the fluid which would be injected. In general, Class I wells include industrial and municipal disposal wells and hazardous waste disposal wells not covered in Class IV; Class II wells include wells which inject fluids 1) brought to the surface during oil and gas production, 2) for enhanced recovery of oil and gas, or 3) for storage of hydrocarbons which are liquid at standard temperature and pressure; Class III wells inject for the purpose of extraction of minerals or energy; Class IV wells include disposal wells used by hazardous and radioactive waste generators and disposal site operators; Class V includes injection wells not covered by the four other classes (146.05). Inherent in the permit process for these injection wells is the "area of review" concept. This concept refers to the lateral distance around an injection well in which pressures developed in the injection formation may cause migration of formation or injection fluid into an underground source of drinking water. The area of review can be determined by calculations using the modified Theis equation or by establishing a fixed radius around the well of not less than 1/4 mile (Thornhill et al., 1982). The method chosen for determining the area of review depends on the appropriateness of each method for the affected geographic area or field (146.06). For the purposes of this report, only those regulations specifically applicable to Class II wells (CFR 40, Part 146 Subpart C) are detailed.

The permitting authority in each state with a UIC program in force or the appropriate regional EPA administrator is charged with determining whether a proposed injection well has a potential for contaminating aquifers through either operating or abandoned wells, or through subsurface geologic features. To assist the permitting authority, the permit applicant must submit (along with other specified information) information on producing wells, other injection wells, abandoned wells, dry holes and water wells within the area of review (146.24). All information on completion and plugging of these wells must also be made available to the permitting authority. The determination must then be made by the permitting authority as to whether conditions may allow migration of contaminants into an aquifer. If it is determined that conditions exist which could allow potential contaminants to migrate into an underground source of drinking water, either the permit is denied or corrective action must be proposed to mitigate the potential for contamination.

In order to determine whether or not migration of potential contaminants will occur from the injection zone into an underground source of drinking water or to effect any corrective action, all wells within the area of review must first be located. If adequate records concerning the construction, abandonment and plugging of the well are available, just recognizing the presence of the well may be adequate. However, if the condition of the abandoned well is not known or if plugging records are inadequate, non-existent or indicators of potential problems, it may be necessary to physically locate the well.

HISTORICAL PERSPECTIVE AND PROBLEM DEFINED

Since 1859, when the first oil well was drilled at Titusville, Pennsylvania until 1981, over 2,750,000 wells were drilled in the United States (Anonymous, 1982a). However, in 1981 only 740,000 wells were producing oil and gas (Anonymous, 1982a and b). What is the status of the other two million wells? Where were they drilled? These questions are only the beginning. In the early days of oil production, dry holes or depleted wells were abandoned without much thought being given to plugging the hole. Often, casing was never set or the casing was removed when the well was not productive (J.T. Thornhill, personal communication, 1983). When a well was "plugged", the plug often consisted of seasoned wood or tree limbs thrown or driven into the hole (Herndon and Smith, 1976). At other times, the well would simply be covered with a board or a piece of sheet metal to help ensure that the well would not become a physical hazard to people or animals (Gass et al., 1977).

Today, every oil producing state has adopted regulations regarding the drilling, plugging and abandonment of wells and the disposal of brines. Often these regulations have been the direct result of surface- or ground-water contamination (Pettyjohn, 1971). However, many of the problems faced today center around the wells which were abandoned years ago.

The potential for an abandoned well to adversely affect ground-water quality depends on the original use of the well, the local geology, the type of well construction and the hydraulic characteristics of the subsurface fluids (Gass et al., 1977). In general, two different types of subsurface injection associated with oil operations can be identified: 1) water flood or pressure maintenance operations and 2) brine disposal operations (McMillion, 1965). The first category involves injection of fluids into a hydrocarbon-producing or former hydrocarbon-producing formation while the second category may involve injection into a hydrocarbon-producing formation or into a non-hydrocarbon-producing formation.

An excerpt from Irwin and Morton (1969) illustrates how abandoned wells which penetrate an injection zone can have a negative impact on ground-water quality. Figure 1 illustrates a situation where formation fluids and injection waters may migrate from an injection formation through abandoned wells into a fresh water formation. Well A represents an injection well where liquid is injected into a permeable zone overlain by impermeable deposits. Well B is an abandoned well which was inadequately cemented in place. Well C represents an abandoned borehole in which no casing was set. In a well such as C, the hole is likely to have caved in partially; however, enough openings may remain to transmit fluid. It is

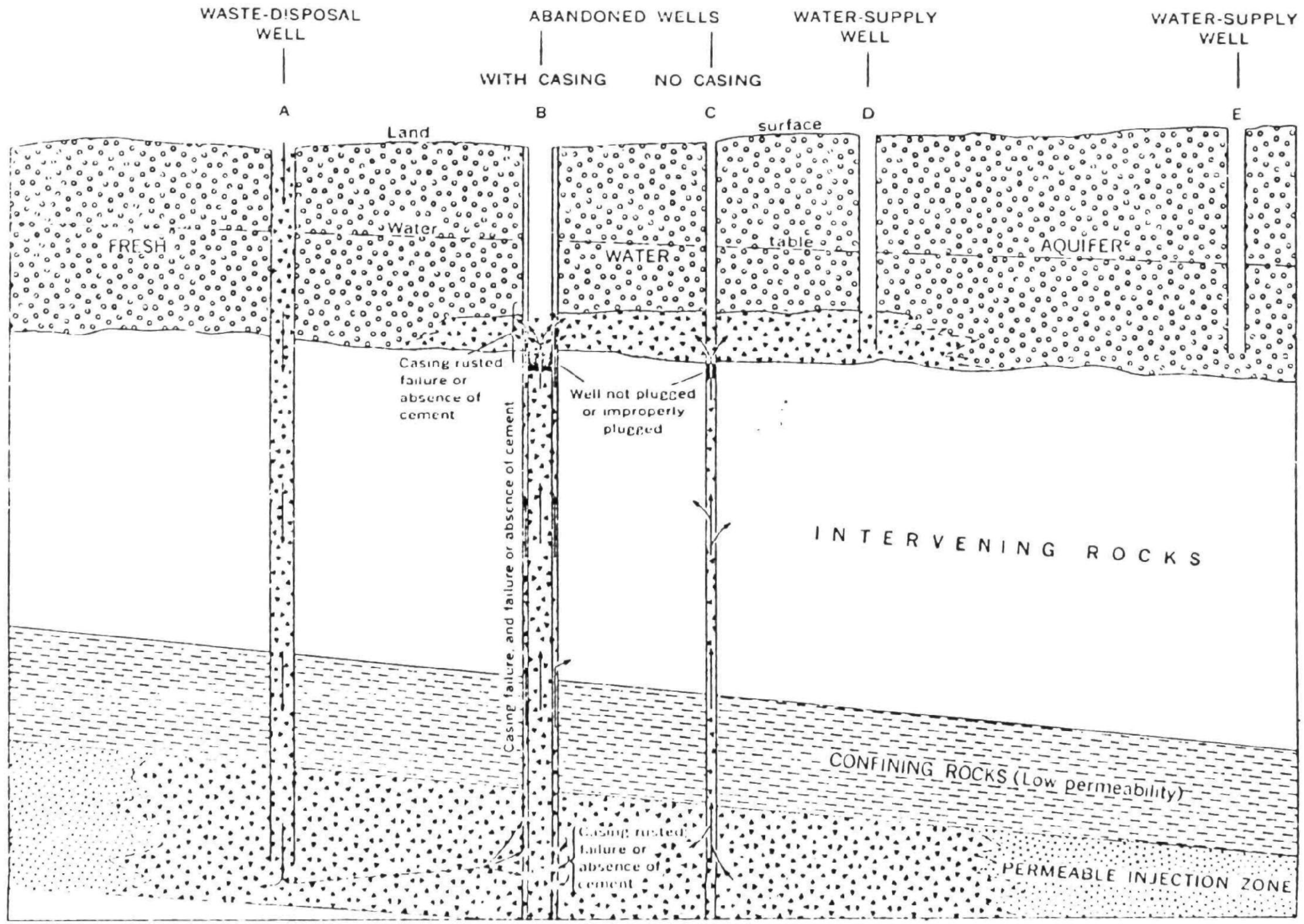

Figure 1. Diagram showing how fluid migration from an injection zone through an abandoned well and into a fresh water zone may occur (Irwin and Morton 1969).

further assumed that neither Well B nor Well C were plugged adequately, if at all. Wells D and E represent water supply wells.

A difference in hydrostatic head within the wells, as shown, could be due to the injection pressure in Well A, the difference in elevation of the top of the injection formation at each well or both. If the head difference is great enough and the potentiometric surface in the injection well is higher than that in Wells B and C (which penetrate the injection formation and are not adequately sealed), the formation and/or waste fluids will migrate upward via wells B and C and enter the fresh-water zone thereby causing contamination of the fresh-water aquifer. From here, the fluids will migrate downgradient and eventually reach the water supply well. This is often the first indication that pollution has occurred. Even if the abandoned hole is located and plugged, the contaminated fluid already present in the fresh-water aquifer will continue to migrate downgradient in the fresh water zone unless some other treatment is employed.

The leakage of contaminated or highly mineralized water upward through abandoned wells and unplugged exploration holes has led to localized ground-water pollution problems in many areas in the United States. According to an EPA report (1973), contamination incidents caused by abandoned or improperly plugged oil and gas wells can probably be found in most oil and gas producing states. McMillion (1965) reports that in Texas "the vertical migration of injected brines from their intended subsurface interval through nearby unplugged or uncased boreholes contributes substantially to (ground water) contamination in many parts of the state". Latta (1963) reports that in Kansas "there are probably hundreds of holes drilled in the state prior to our plugging laws that were left unplugged or were improperly plugged. Where the pressure is sufficient, either natural pressure or pressure created by repressuring projects, brines may come up these holes from deeper formations and escape into fresh-water zones or to the surface". Gogle (personal communication, 1983) states that in Ohio "when well stimulation is initiated, it is not uncommon for abandoned wells to appear where no surface expression was previously evident".

One of the most illustrative examples of problems associated with injection in an area containing abandoned wells that were improperly plugged is cited by Hopkins (1963). In east-central Kentucky, a pressurized injection well was located about 200 feet away from a gas well used for domestic fuel. Upon initiation of injection operations, the gas furnace in the living room of the farmhouse spouted brine. After injection was stopped, the flow ceased.

While instances such as these have been documented in the literature, the scientific community and the state regulatory agencies have only recently realized the potential magnitude of the problems created by improperly abandoned water, gas and oil wells (Gass et al., 1977). To ensure that these types of problems do not occur, all operating wells and abandoned wells within the area of influence of injection wells must be accurately located and their status determined.

PROBLEM ASSESSED

Traditionally, abandoned wells were located only when a ground or surface-water contamination problem was identified or when an economic incentive existed for a certain industry to locate and plug the well. Abandoned wells needed to be located and plugged in coal-mining areas because the abandoned, unplugged hole may serve as a source of both unwanted water and gas, and thereby pose a potential hazard to the ventilation system within the mine (Roley, 1949). In gas storage fields, abandoned wells may provide an outlet for the injected natural gas. For example, 25 abandoned wells were located and plugged within a 2560 acre gas storage field in Grant County, Oklahoma when it became apparent that the abandoned wells would cause a problem (Herndon and Smith, 1976).

In developing Methods for Determining the Location of Abandoned Wells, past, present and potentially available methods for locating abandoned wells were researched. Government officials in oil and gas producing states were surveyed regarding regulations, requirements and methods used by the agency to locate abandoned wells (see Appendix A). Efforts to document methods used by industries such as oil and gas companies or mining companies were conducted. Attempts were also made to assess the applicability of many types of equipment for locating abandoned wells and to identify the availability of companies able to perform abandoned well searches.

It was apparent that three types of searches, either separate or in combination, could be performed to locate and assess the status of an abandoned well. First, an area overview to locate the presence of an abandoned well within a certain area could be performed. Second, a more detailed search to establish the status and establish the potential impact of that well could be conducted. Third, an attempt could be made to actually field locate the well. This manual attempts to address methods which can be used in all three types of searches.

ORGANIZATION

This document contains two parts, eighteen sections, and two supporting appendices. The development of the sections and appendices are user-oriented. Sections 4-11 address methods of locating abandoned wells which have been historically used and also contains information on new ways to apply these methods. The sequence of the presented methods approximates the order that the methods would be used to identify, generally to specifically, the location of an abandoned well. Sections 12-18 address technologies which may not have been specifically developed for locating abandoned wells, but which may have future application. A variety of methods in many combinations may be useful or necessary in the final endeavor.

An attempt has been made to summarize applicable techniques and technologies throughout the manual. Each section contains a reference section for additional information.

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SECTION 2

CONCLUSIONS

Improperly plugged or unplugged abandoned wells which penetrate an injection formation may provide a conduit for migration of injected fluids into fresh water formations. With the adoption of the Federal Underground Injection Control Regulations (UIC), all abandoned wells within an "area of review" around a proposed injection well must be located. This will help to ensure that if an abandoned well is present, the potential for contamination of the fresh water through the abandoned well is minimized.

To date, few methods have been successfully used to search for abandoned wells. Most searches have employed a combination of record searching, talking with residents, looking for the well and walking over the area with a metal detector or magnetometer. While few methods have actually been used, a variety of other technologies, although not specifically developed for this purpose may be useful in searching for abandoned wells. Geophysical methods such as electrical resistivity, electromagnetic conductivity and ground penetrating radar all may have various applications in searching for abandoned wells. Remote sensing techniques, including black and white aerial photographs, color photographs, color infrared and thermal infrared may be combined with other methods to provide a different dimension to the search. Other more indirect methods such as water-level measurements or actual injection may also be applicable in certain situations.

A search for abandoned wells may have three different objectives: 1) to provide an overview of the presence or absence of abandoned wells within an area, 2) to determine the status of a particular well and establish the potential impact of that well, and 3) to actually field locate the abandoned well. The scope of a search may encompass all or any combination of these objectives before the search is completed.

Since many different methods may be employed in the search for abandoned wells, the applicability, advantages and disadvantages of each method must be understood to facilitate a rational decision regarding which technique or combination of techniques can be applied to each individual situation. Table 1 provides a detailed summary of the methods which have been used in the past and the methods which may be applicable for use in searches for abandoned wells. The best combination of methods depends on the objectives of the search, the condition and surface expression of the abandoned well and the resources available to conduct the search.

Table 1. SUMMARY OF APPLICATION, ADVANTAGES AND DISADVANTAGES OF EACH METHOD WHICH MAY BE USED TO LOCATE ABANDONED WELLS

Method	Application	Advantages	Disadvantages
Search of records	Cased/uncased wells	Provides overview of area May provide enough information that no further search is needed	Records may be unavailable or incomplete May not be able to determine location or match development/plugging records with location Well locations may be inaccurate
Conversations with local residents	Cased/uncased wells	May reduce field search time Information may not be available from other sources May actually point out location of well	Residents may not know information May be time consuming without results
Visual/Logical	Cased/uncased wells	Location may be determined without equipment	Requires recognizable surface expression
Aerial Photographic Interpretation	Cased/uncased wells Surface disturbance by drilling activities	Historical photographs may actually "capture" drilling operation Historical photographs may show surface features which have since been obliterated Aerial perspective may show features not evident on the ground	May not be available There may be no surface expression on photos Still requires field location
Metal detectors	Cased wells Metal objects associated with drilling	Can find buried metal objects or casing Equipment inexpensive No specific training necessary to operate equipment Equipment portable Provides continuous readings Suitable for all terrain and vegetative cover No interpretation of data necessary	Limited to metal casing or objects at shallow depths
Magnetometers a. surface	Cased wells Ferrous metal objects	Can locate buried metal objects or casing Some equipment easy to operate, has direct output and requires no interpretation Some inexpensive equipment available Portable and suitable for all types of terrain and vegetative cover	Limited to metal casing or objects at shallow depths Some equipment requires experienced operator Some equipment produces data which may require limited interpretation Readings may be affected by cultural features

(continued)

Table 1. (continued)

Method	Application	Advantages	Disadvantages
Magnetometers b aerial	Cased wells	May provide location of either buried or unburied casing May provide overview of presence of cased wells in an area	Requires special survey Aircraft needs to be flown at low elevations Readings affected by cultural features Limited to low population density rural areas Requires interpretation of data by professional
c subsurface	Cased wells	Determine location and depth of casing in a well May be used to locate casing at great depths	Requires the presence or construction of an uncased hole within 15 feet of the abandoned well Requires services of professional company Expensive
Methane detectors	Cased/uncased wells	Equipment inexpensive and easy to operate Equipment portable Suitable for all types of terrain and vegetative cover	Must have detectable presence of gas at surface Wind may disperse gas
Excavation	Cased/uncased wells	Provides verification of a buried well location that is determined by other methods	May excavate large areas without results
Electrical resistivity	Cased wells	May locate buried casing Not limited to very shallow depths but may be more successful at shallow depths	Limited to finding casing Requires special expertise to conduct survey Electrodes must be inserted into ground to obtain readings Cannot be used in all terrain or vegetative cover Less cost effective than other methods for finding cased wells Relatively slow
	Saline ground-water contamination plumes	May locate ground-water contamination plume from an abandoned well	All above disadvantages applicable Requires interpretation of the data Contamination may be due to other sources Requires additional methods to verify location of well

(continued)

Table 1. (continued)

Method	Application	Advantages	Disadvantages
Electromagnetic conductivity	Cased wells Soil disturbances associated with drilling Saline ground-water contamination plumes	Equipment portable Suitable for all types of terrain and vegetative cover Not limited to shallow depths Readings obtained as quickly as area can be traversed on foot	Requires special expertise to conduct survey Equipment expensive Interpretation of data may be necessary Contamination may be due to other sources Soil disturbances must be larger than a borehole Other methods may be needed to verify well location
Ground penetrating radar	Cased/uncased wells Metal objects Soil disturbances	May provide location of either buried cased/uncased wells, metal objects or soil disturbances associated with drilling Rapid survey with truck mounted equipment Equipment provides continuous readings Depth penetration of 10 to 25 feet common On-site interpretation possible through graphic recorder	Vegetation must be low or cleared from site Access for vehicle or hand towing must be provided Requires professional company Additional interpretation of data necessary Must pass over casing to detect Relatively expensive
Remote sensing	Cased/uncased wells Surface disturbances by drilling activities Vegetative stress	Color infrared may help show all features by responding to electromagnetic radiation May provide aerial overview May be able to see different surface features than could be seen with regular photographs	Imagery not already available Requires special survey Survey expensive Requires interpretation of photographs Thermal infrared may not be applicable Field location still necessary

(continued)

Table 1. (continued)

Method	Application	Advantages	Disadvantages
Water level measurement in surrounding wells	Cased/uncased wells	No specialized equipment necessary May determine presence of well when other methods not successful	Requires local hydrogeologic information Existing wells may not be close enough to abandoned well Only can be used when migration from lower formations occurs Still requires field location by other methods
Injection	Cased/uncased wells	May produce surface expression of the well No further location methods needed	Pressure in subsurface must be great enough to cause migration of fluid to surface Channel must be well defined and close enough to ground for fluid to appear at surface May not be evident immediately after injection starts

SECTION 3

RECOMMENDATIONS

A search for an abandoned well may employ more than one method to determine its location. The following list of procedures should be used to help establish a systematic approach to finding abandoned wells:

1) Any search for abandoned wells should begin with a search of the available records;
2) The scope of the search should be defined and the advantages and disadvantages of each method should be evaluated within the objectives of the search;
3) The area of the search should be narrowed as much as possible before field methods are employed;
4) The most cost-effective method for the situation should always be employed first.
5) The level of effort spent in trying to locate the well should be commensurate with the potential for contamination from the well; and
6) There is a point when it is not cost effective to continue search efforts for the abandoned well.

Because many of the technologies detailed in this report have not been specifically applied to locating abandoned wells, further study is needed in the following areas:

1) The ground-based geophysical techniques of electrical resistivity, electromagnetic conductance and ground penetrating radar should be field tested for this application. The testing of ground penetrating radar is particularly important because it is one of the few methods which can be used to locate uncased abandoned wells.

2) The aerial searching methods should be field tested to determine the viability of discovering the location of abandoned wells in overflights. Aerial magnetometer searches and color infrared imagery may prove the most successful.

3) Interpretation techniques for both aerial photography and color infrared imagery should be refined and signatures for activities associated with drilling should be developed for selected locations at selected historical time intervals.

4) Research into new methods for locating abandoned wells should be encouraged.

SECTION 4

SEARCH OF RECORDS

SYNOPSIS

Information related to oil and gas well-drilling activities may be available from state regulatory agency records, county courthouse records of oil and gas leasing agreements, county tax records, oil company records or service company records and private companies which sell logs. The completeness of the available records will be influenced by the date the well was drilled and the requirements (if any) in effect at the time. A search of available records provides, at the very least, a generalized picture of drilling activity within a given area and may provide enough detailed information to adequately determine the status of a well or to actually field locate the well. While the cost associated with obtaining copies of the pertinent data may be small, the manpower requirement necessary to obtain the information will vary according to the organization of the record keeping system as well as the familiarity of the individual with that system.

DISCUSSION AND PROCEDURES

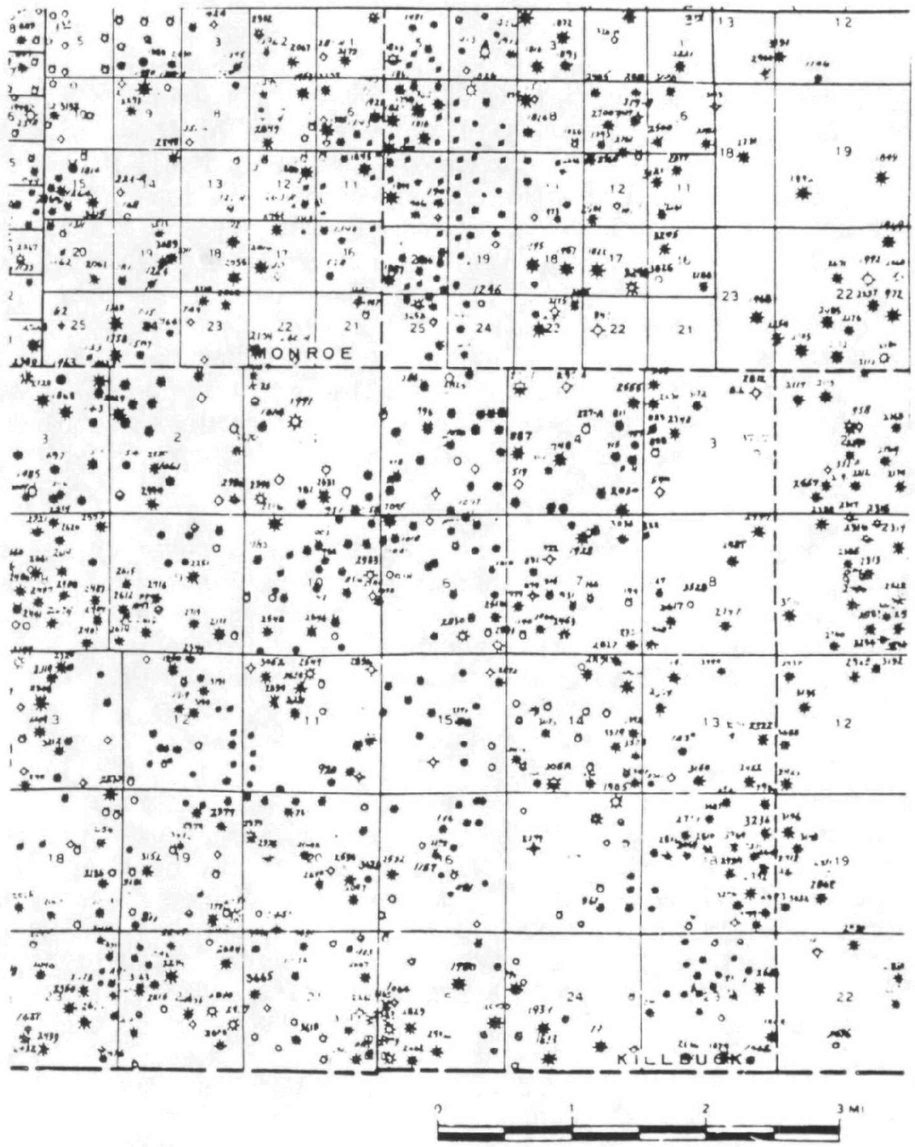
The search for abandoned wells should begin with a search of all available records. Information related to oil and gas well-drilling activities may be available from a variety of sources, including state regulatory agency records, county courthouse records of leasing agreements, county tax records, oil company records or service company records and private companies which sell logs. The information available will vary from source to source and also may vary with the age of the well or well field.

State agencies often possess the most complete and readily available source of information on oil and gas drilling activities. To determine the extent of information available and to determine which agency had adopted the primary role in oil and gas activities, a survey of the 38 states with producing oil and gas wells was conducted (see Appendix A). A records search in each of those states should begin with the agency listed in Appendix B. These agencies have been identified as the depository of well logs in each of the respective states.

An overall assessment of oil and gas activity within a specified area can be obtained by viewing maps which have been prepared to show well locations within an area. Of the 38 states surveyed, 79 percent responded that centralized maps with well locations were compiled. In the states which do not compile maps, private companies may perform this function. The maps which are compiled by the states are available in a variety of scales and are graphically depicted in many different ways. Figure 2 illustrates the oil and gas producing wells in one county of one of the states surveyed. The map depicts the status of each well (if known) and the permit number (if assigned). Wells may also be plotted on United States Geological Survey (USGS) topographic maps, township maps or on county tax maps. Figure 3 is plotted on a county tax map and depicts wells which were drilled around 1885 and for which drilling and status records are scarce. In comparison, Figure 4 is plotted on a township map and illustrates the visual display of information which is commonly available for more recently drilled wells. The symbols used on maps such as these vary from state to state. According to the U.S. Department of Housing and Urban Development (1982), "there is no single set of universally accepted oil and gas well mapping symbols". However, the American Petroleum Institute has developed a standard set of symbols (Figure 5) which are becoming more widely accepted.

Once a general assessment has been made, a more detailed search for information either on the well itself or well location may be warranted. Information regarding location, completion, plugging and abandonment of a well may be available from state agencies in a variety of ways. Records may be stored in paper files, on microfiche, on computer or may be combined in any of these filing and retrieval mechanisms. Information may be filed according to permit number, county, oil field, landowner, operator, lease or other methods. Records for each well may be kept in one file or may be available from a multi-file cross-reference system. The filing system for a state may change after a specified date due to a change in the record-keeping system. An example of the way information may be filed by one state agency is detailed below: "To access the required records, one must first locate the well on the township and range map. After the well has been located, a permanent serial number will be noted adjacent to the well. With this serial number, the central records staff can access the microfiche that will have all forms filed with the state on the well. Since the serial number is permanent, no additional research is required in the case of operator name changes due to lease purchases or the reentry of old wells by new operators" (Lennon, personal communication, 1983). The retrieval system is so specific to each state that the state office listed in Appendix B should be contacted to obtain further information.

Information on the location of wells is available through this record-searching process. Specific requirements for the designation and description of the well varies from state to state and through time. In general, the well location is designated by reference to township and range, section, roads, lot lines or other boundaries and physical features which should permit location of the well. The series of figures described below depicts some of the ways the location of a well may be designated. Figure 6 illustrates a detailed plot prepared by a registered surveyor which clearly depicts the location of the well with respect to section lines, lot lines and nearby roads. Figure 7 illustrates the location of wells with respect to section lines, but the actual well location is not



WELL SYMBOLS

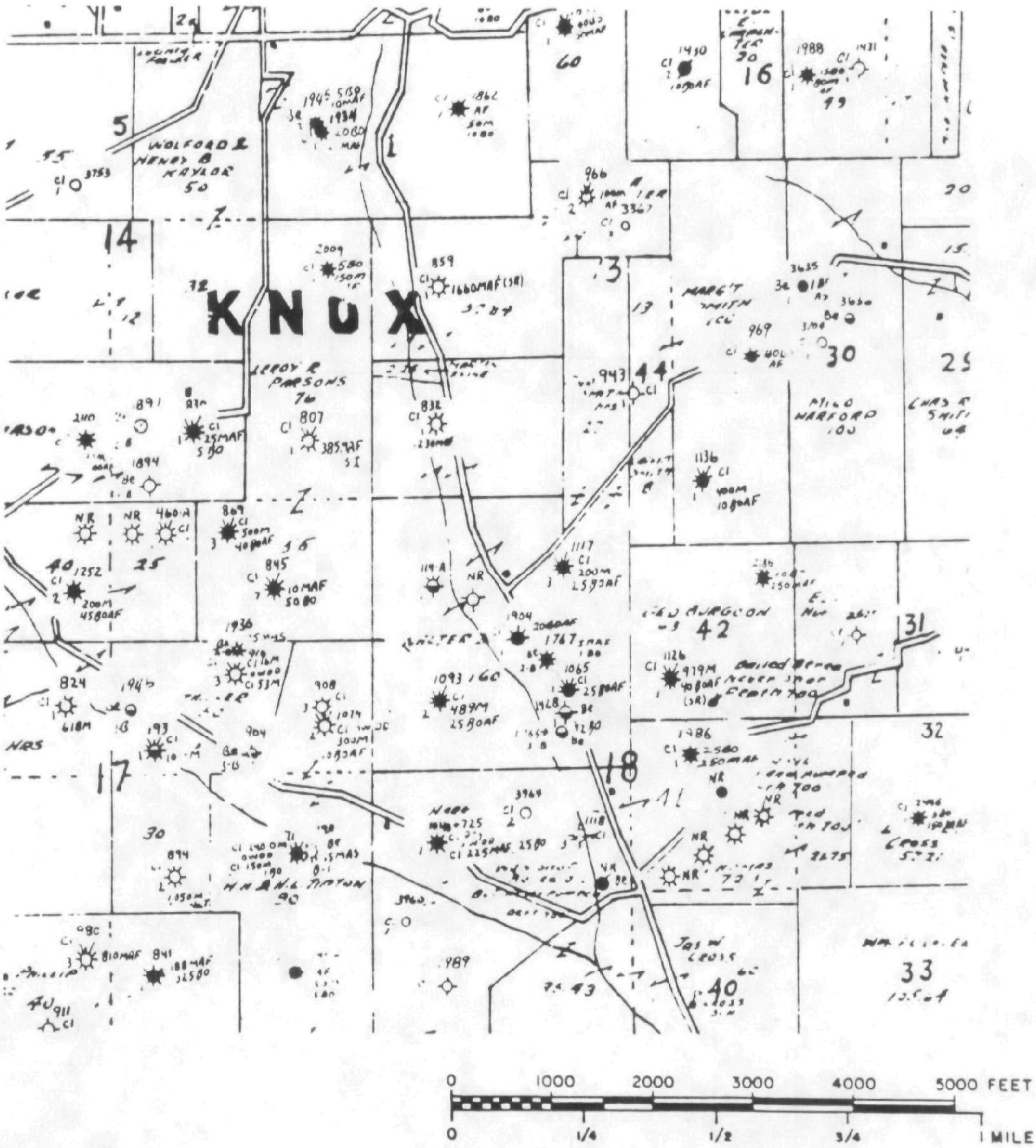
- location
- abandoned location
- gas well
- gas well; show of oil
- abandoned gas well
- oil well
- oil and gas well
- oil well; show of gas
- abandoned oil well
- dry hole
- dry hole; show of gas
- dry hole; show of oil
- dry hole; show of gas and oil
- production from two or more horizons

Figure 2. Part of a county map showing the location of oil and gas wells.

WELL SYMBOLS

- location
- abandoned location
- gas well
- gas well; show of oil
- abandoned gas well
- oil well
- oil and gas well
- oil well; show of gas
- abandoned oil well
- dry hole
- dry hole; show of gas
- dry hole; show of oil
- dry hole; show of gas and oil
- production from two or more horizons

Figure 3. Part of a county tax map showing wells drilled around 1885.



WELL SYMBOLS

- location
- abandoned location
- gas well
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- abandoned gas well
- oil well
- oil and gas well
- oil well; show of gas
- abandoned oil well
- dry hole
- dry hole; show of gas
- dry hole; show of oil
- dry hole; show of gas and oil
- production from two or more horizons

Figure 4. Part of a township map illustrating typical platted information for more recent wells.

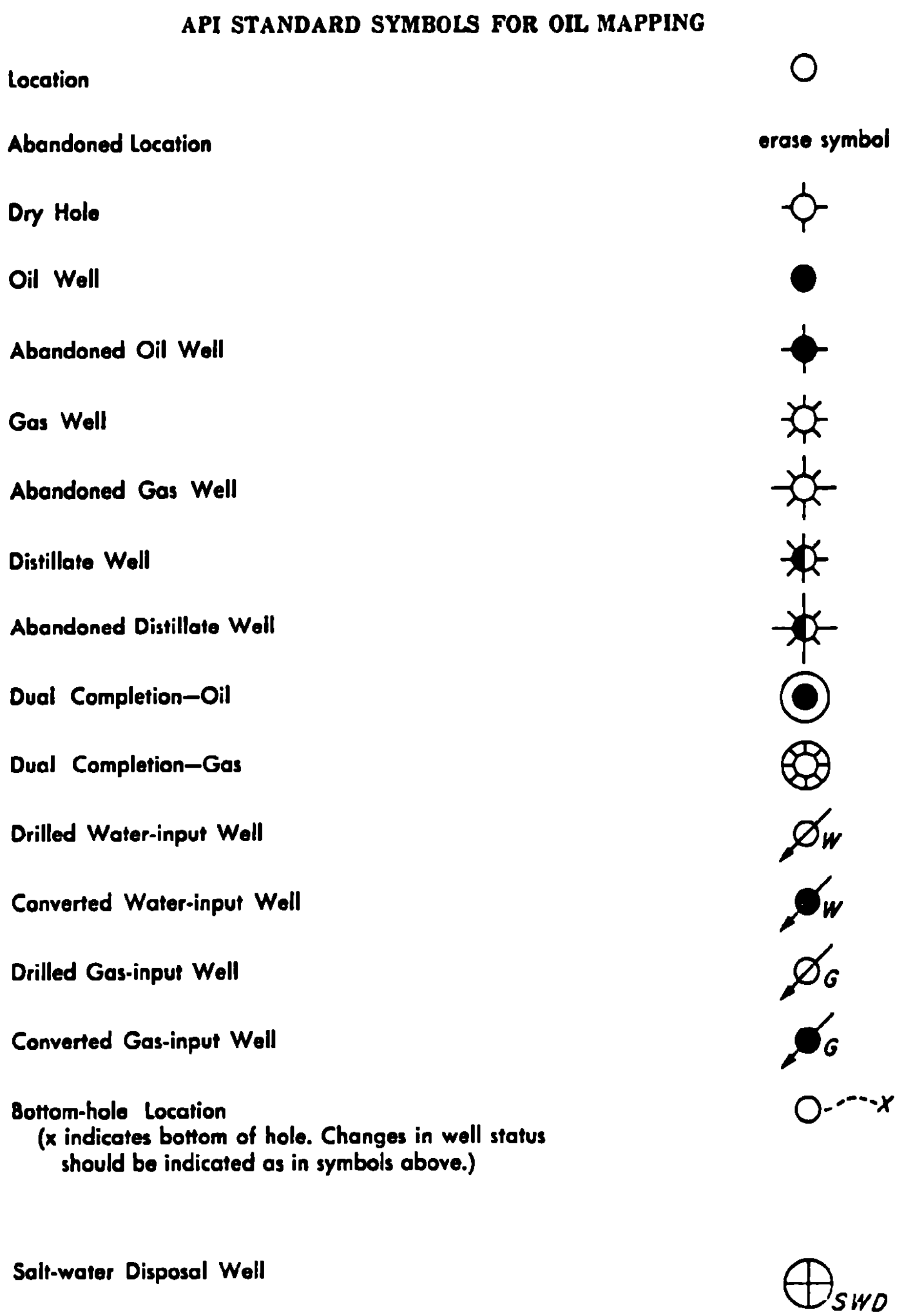


Figure 5. American Petroleum Institute standard map symbols.

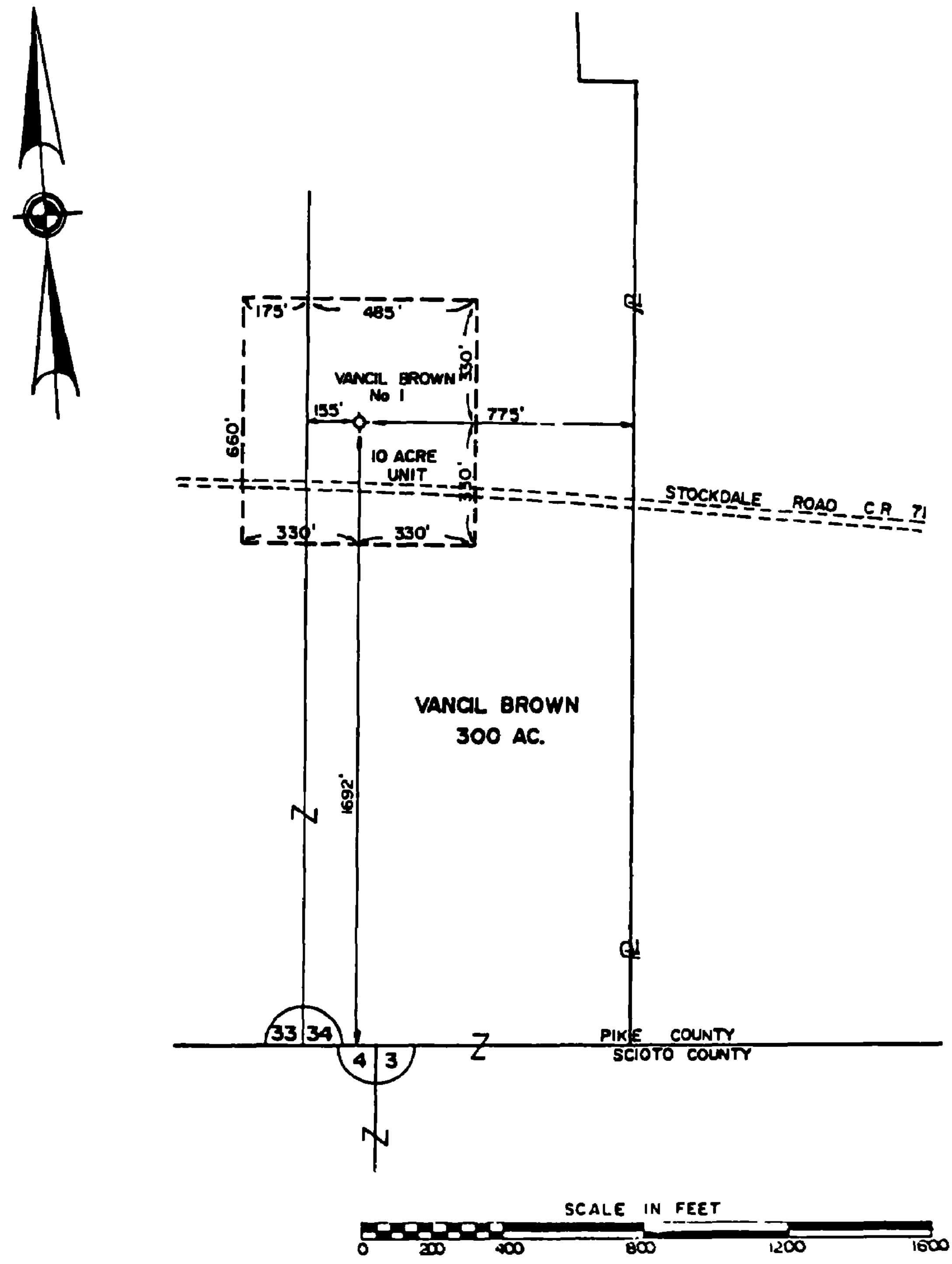


Figure 6. Detailed location map clearly showing the location of the well.

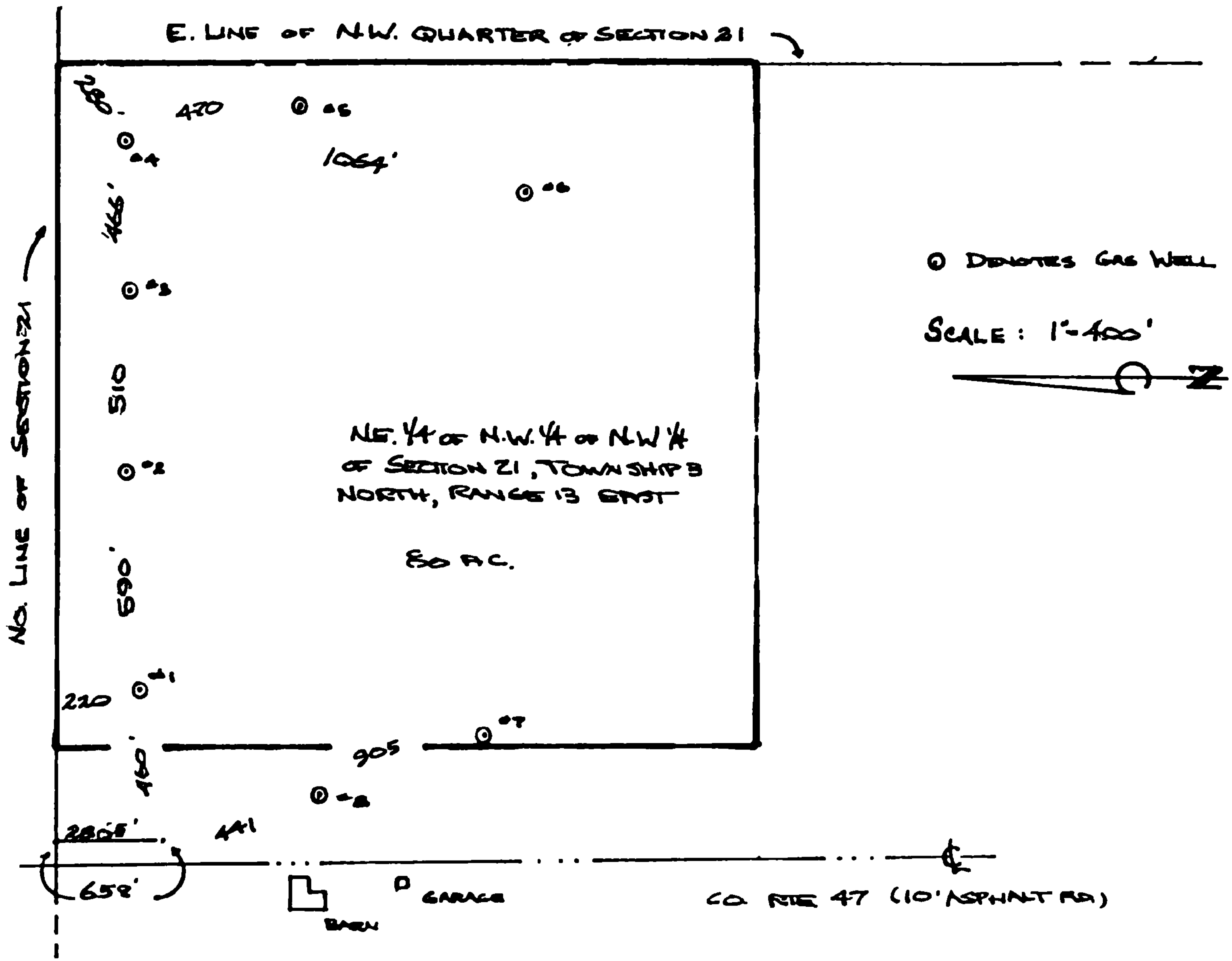


Figure 7. Location map showing an example of a well location which is not clearly defined

clearly defined. Figure 8 illustrates the well with respect only to local roads. Oftentimes, a detailed plot will not exist at all for older wells. According to Fairchild (1983), who searched historical records of the Oklahoma Corporation Commission, it was possible to determine some well locations within 1/64th of a section, while other locations could only be determined as being somewhere within a section. It is obvious that some wells might very easily be field located from a given description, while other descriptions may not provide enough information to locate a well without first obtaining further information.

Information on the completion, plugging and abandonment of wells may also be available from the appropriate state agency. Most state regulations require the submission of this information on state approved forms. Information such as the depth of casing, whether the casing was left in the ground when the well was abandoned and the type and method of emplacement of the plug(s) may be available in the files. This data may be necessary to evaluate the status of the well and to determine if the well was adequately plugged.

Additional information may be available from a variety of other sources. Well location information may be available from oil and gas companies which maintain their own records of producing wells or who have historic data on other wells or well fields. Independent contractors and operators may also have records available. Libraries may have documents which have compiled data from historic sources and independent oil and gas record-keeping companies may have information on the location of wells. County tax records and county courthouse records of leasing agreements may provide information about the location of a well and/or may also assist in identifying an owner, operator or lease holder which is vital in a record cross-check. Service companies may be an additional source of information for completion or plugging reports which are not available from other sources.

COST

The cost of a record search is directly proportional to the amount of time or manpower required to complete the search. This, in turn, is related to the number of wells being researched, the information needed for each well, the familiarity of the individual with the filing and retrieval system and the ease of access to that system. In addition to the manpower requirement, reproduction charges for logs, maps, completion reports, plugging reports, etc. must also be taken into account. Most public agencies make copies available for a nominal charge of $0.10 per paper copy and $0.20 for microfiche. Publications and maps are usually available for a reasonable cost. Libraries, oil and gas companies and other sources generally charge only reproduction costs or at most, personnel charges for the time spent researching the required information. The charges by an independent record keeping company vary according to the amount and type of information requested.

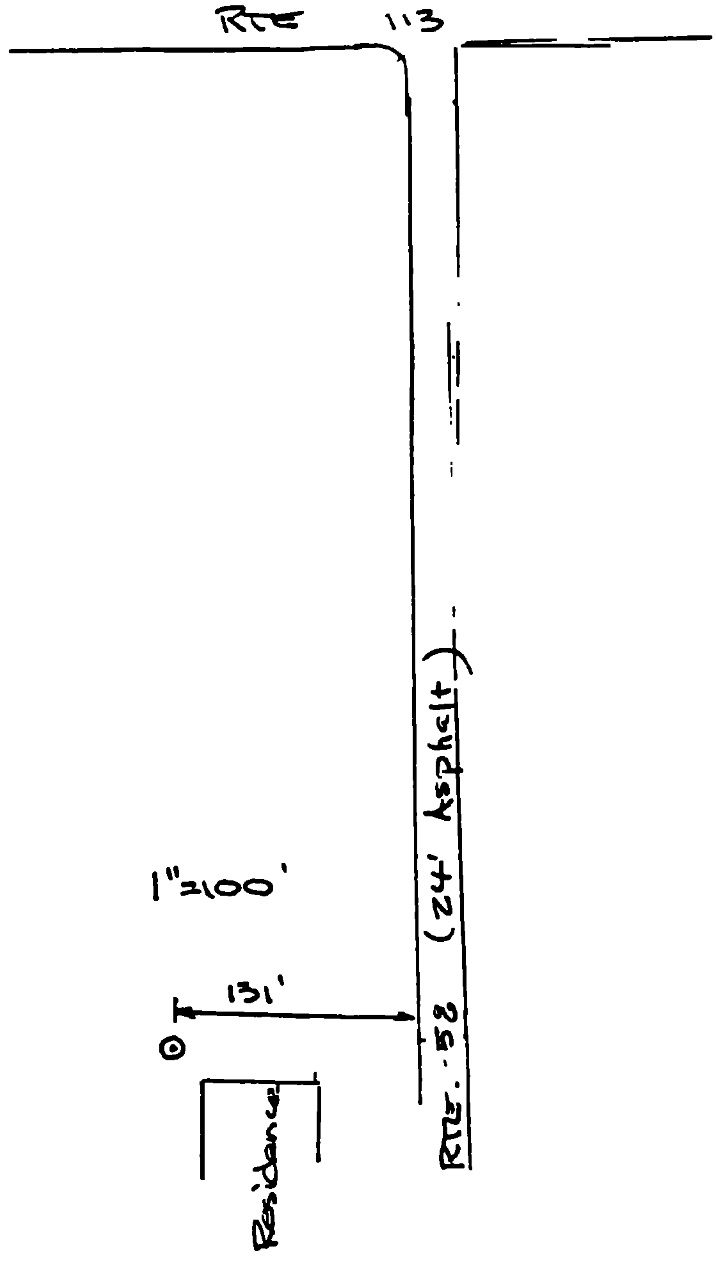


Figure 8. Well location map which leaves the location to the imagination of the interpreter.

Professional record searching companies provide an alternative to self-searches in some states. These companies are familiar with the record filing system of each agency and charge fees to perform the service. A typical charge would be $25.00 per hour plus reproduction charges. Representative reproduction charges would be:

paper (letter and legal)	$0.60 each
microfilm prints	$0.60 each
electric logs	$1.00/foot
oversize prints	$1.00 each

ADVANTAGES AND DISADVANTAGES

Record searching is the starting point for determining the location or status of any abandoned well. It provides, at the very least, a general picture of drilling activity within a given area and may provide enough detailed information to determine the status of wells or to actually field locate the well. The record search, however, does provide the preliminary analysis necessary to determine if further investigation is necessary. The disadvantages are not related to the method itself, but rather to the incompleteness of the records. At times the records may not be available, the well status may be unknown or it may be impossible to match well-plugging reports with the appropriate well location. Well locations may be inaccurate or impossible to interpret. In spite of these inadequacies which are exemplified in the older wells, the records provide a starting place for further investigations.

CASE HISTORIES

Searches of records may be performed for a variety of reasons. The case histories listed below provide examples of reasons that searches were conducted and detail the success of those searches in obtaining the desired information.

Case #1

A study in Oklahoma (Canter, 1981) sought to inventory the oil and gas activities in 80 townships overlying the Garber-Wellington aquifer to assess their potential for causing ground-water pollution. To achieve this goal, records were assembled on oil and gas wells which had been drilled since records were kept by the Oklahoma Corporation Commission in 1917. It was determined that 14,127 oil and gas wells were drilled since 1917 in the 80-township study area. In addition, the date of drilling, depth of well, surface casing, plugging reports and other information was compiled (when available) for these wells. From this information, areas were rated by their potential for ground-water contamination.

Although the inventory and record search was not the prime thrust of the report, the quality of the information had a direct bearing on the output. According to the report, the biggest problems encountered in record searching were the incompleteness of the plugging reports, the lack of specifity as to well location and the difficulty in matching records to determine if they belonged with the same well.

Case #2

Another study conducted in Tulsa County, Oklahoma prepared by the U.S. Department of Housing and Urban Development (1982) sought to determine the effects of abandoned oil and gas well locations on housing sites. After searching records for information such as the location, depth, casing program, plugging program, date drilled, date plugged and operator, four main problem areas were identified: 1) inability to accurately locate the wells; 2) problem of confusion in the numbering system of historic wells (prior to 1966); 3) lack of adequate plugging records and 4) unavailable or incomplete records of historic wells and well fields.

Case #3

Information from Texas Railroad Commission files indicates that an oil and gas corporation filed a request for a fluid injection permit in Cooke County, Texas. As part of the permit process, all wells and their status within a 1/4-mile radius that penetrated the top of the injection zone needed to be identified. Table 2 indicates the information obtained for wells by a record search of the regulatory agency. Four wells were identified as having no record of the current status. Field inspections and further record searches yielded the following results:

1. Wells #2 and #4 of Lease D were field located and the plugging reports were obtained.
2. Well #1 of Lease E contained a 7-inch casing open at the ground surface with a fluid level at 6 feet.
3. Well #2 of Lease E contained a 7-inch casing open at the ground surface and a fluid level at 350 feet.

The two open wells on Lease E were subsequently plugged and the permit was issued.

Table 2. SUMMARY OF WELLS AND WELL STATUS WITHIN AN AREA OF REVIEW, CASE HISTORY #2.

Lease A/Well No.	Date Drilled	Current Status
1	9-35	P & A*
2	7-36	P & A
3	3-37	Producing
4	4-37	P & A
5	5-37	Producing
6	5-37	P & A
7	5-37	Producing
8	6-37	P & A
9	7-37	P & A
10	9-37	Producing
11	2-38	Producing
12	2-38	P & A
13	3-38	P & A
14	4-38	Producing
15	4-38	Injector
16	5-38	P & A
17	5-38	Producing
18	7-38	P & A
19	6-54	Subject Well
20	7-54	Producing
21	9-54	Producing
22	1-55	Producing
23	11-55	Producing
24	12-56	Shut-in
25	12-65	Injector

Lease B/Well No.	Date Drilled	Current Status
2	9-35	P & A
3	10-35	P & A
4	11-35	P & A
5	12-35	P & A
6	8-37	Injector
7	8-37	Producing
8	9-37	Disposal
9	10-37	Producing
10	11-37	Producing
11	1-38	P & A
12	6-38	Producing
13	7-39	P & A
14	11-39	Producing
17	7-54	Producing
19	7-54	Shut-in
20	10-54	Injector
22	1956	Producing
23	5-56	Injector
24	8-56	Producing
25	12-56	Producing
26	1-57	Shut-in
27	5-60	Shut-in
28	8-61	Producing
29	11-62	Producing
30	12-64	Producing
32	6-66	Producing
33	6-66	Producing
34	6-68	Producing

Lease C/Well No.	Date Drilled	Current Status
7	3-55	Shut-in
8	6-37	P & A
9	No Data	Producing
10	No Data	Shut-in
11	No Data	Producing

(continued)

Table 2. (continued)

Lease D/Well No.	Date Drilled	Current Status
2	8-33	No Data
4	9-35	No Data
Lease E/Well No.	**Date Drilled**	**Current Status**
1	No Data	No Data
2	No Data	No Data
3	9-33	P & A
4	4-38	Producing
5	5-38	P & A
7	6-38	Producing
10	—	Producing
11	1-66	Injector
12	5-66	Injector
14	6-81	Producing
Lease F/Well No.	**Date Drilled**	**Current Status**
12	10-35	Producing

*P & A means plugged and abandoned

REFERENCES

Canter, L., 1981, Empirical assessment methodology: Prioritization of the ground-water pollution potential of oil and gas field activities in the Garber Wellington area; Unpublished manuscript, for the U.S. EPA.

Fairchild, Deborah, 1983, Selection of flight paths for magnetometer survey of wells; Unpublished manuscript, 9 pp.

U.S. Department of Housing and Urban Development, 1982, The potential effects of historic oil and gas well locations on housing sites; U.S. Department of Housing and Urban Development Region VI, 142 pp.

SECTION 5

CONVERSATION WITH LOCAL RESIDENTS

SYNOPSIS

Property owners, "old timers", local residents or former oil field workers may be able to provide information concerning the location and number of abandoned wells within a specific area. This, in turn, may help to verify the accuracy and completeness of information obtained from a record search, may narrow the area which needs to be intensively searched by other methods, or may actually pinpoint a well location. While the effort expended to obtain the information depends on the number of individuals interviewed and their knowledge of past drilling activities in the area, the information is often not available from any other source. Information obtained from residents may significantly reduce the cost of further searches.

DISCUSSION AND PROCEDURES

Conversations with local residents concerning past drilling activities may be coupled with other search methods to assist in locating abandoned wells. When record searches yield data on well locations which are not specific or which cannot be easily identified, a property owner may be able to recall the actual drilling of the well or be able to pinpoint the specific well location. If this is not possible, residents may be able to provide a general description of a well location such as "in the northwest corner of the plowed field" which may be used to determine the presence of an abandoned well, further define a suspected well location or narrow the area which needs to be searched by other methods for exact location.

Older residents or former oil-field workers may be able to provide information about landowners, drillers or companies involved in the drilling process. This information may be helpful in further record searching. Additionally, the "old timers" may be able to provide information about the years that well drilling took place in the area and the drilling methods and techniques that were used. This may assist in selecting specific years of aerial photographs which should be reviewed (refer to Aerial Photographic Interpretation, Section 7).

When conducting a survey of local residents, good rapport is necessary. Explanation of the reason for the search as well as an indication of the importance of the information is imperative. Without this knowledge and understanding, a local resident may not wish to divulge the information.

Surveys may be conducted by mail, telephone, via the media (radio, television) or in person. Media support may help in alerting residents that information is needed and that a representative may be contacting them. Response to mail surveys is traditionally poor, but may provide a basis for further contacts. Although telephone surveys may be necessary, personal contact often provides the most complete information.

Contacts with local residents are often more informative if another respected local resident or person familiar with the general area speaks with the residents or is present during the interview. A good listener and someone who interacts well with people is a prerequisite for the job which often entails listening to hours of stories in order to obtain the desired information.

COST

The cost of conducting conversations with local residents is related to the amount of time and manpower necessary to complete the discussions. This depends on the number of individuals contacted, the method used to conduct the survey and the amount of time spent conversing with each individual.

The largest cost is associated with the salary of the personnel conducting the interviews since material costs such as postage can be kept to a minimum and media coverage may often be available for minimal costs in a public service announcement.

ADVANTAGES AND DISADVANTAGES

Local residents may provide valuable information about the presence, location or status of wells within an area which may not be recorded or readily available from another source. This information may prove helpful in conducting further searches or in reducing the amount of time necessary for additional searches. The effort and resources expended to obtain this information vary greatly, but can be easily controlled since the only cost is directly related to the manpower necessary to conduct the interviews.

The disadvantages are not related to the method itself, but rather to the knowledge of the individuals and their willingness to cooperate. At times, the desired information may not be known by the individuals questioned. In spite of this, however, the method should be employed whenever possible.

CASE HISTORY

Efforts to locate an abandoned well suspected of contributing to a ground-water contamination problem in Callahan County, Texas had been substantive, but unsuccessful. Records indicated that a dry hole had been drilled and subsequently plugged in 1954. In an effort to locate the well, the lease location had been measured in, a metal detector had been used to search the area and shovels had been used to excavate at various locations. Most of the residents had been contacted to request their assistance in determining the exact location of the well and none were able to point out the exact location. The last option was to simply excavate in the general area until the well was found. This option could have entailed a considerable amount of excavation and expenditure of funds.

The problem was solved when a landowner in the concerned area contacted officials and indicated that he could show them the exact location of the well. The landowner claimed that when he purchased the land, the casing of the well was visible at the ground surface. The area had since been filled and a caliche road had been constructed over the site of the well. The landowner indicated that the well would be in the middle of the road and under one to two feet of soil and caliche. Upon excavation of the site by a backhoe, the casing was located and the well was reentered and subsequently plugged even though the contribution of the well to the ground-water contamination problem was never determined (Texas Railroad Commission files).

SECTION 6

VISUAL/LOGICAL

SYNOPSIS

Field location of abandoned oil and gas wells can be accomplished by visually identifying the well location or by identifying clues and equipment associated with well drilling and production activities. The assembly of all information obtained from other searches and the employment of other methods which use specific equipment enhance and compliment the success of any field search. A field search ultimately produces the identification of the well location or the edict that the well cannot be located at this time. The manpower necessary to complete the search will vary according to the area searched, the methods employed, the remaining surface expression of drilling and production activities and the success in locating the well within an acceptable time frame.

DISCUSSION AND PROCEDURE

When preliminary investigations indicate that there may be abandoned wells in the area or when the status of an abandoned well is not known, it may be necessary to physically locate the abandoned well. A review of information obtained from record searches, aerial photographs and conversations with residents when coupled with a knowledge of drilling procedures, equipment and practices can help to narrow a search area and familiarize an individual with visual clues to well location.

Some abandoned wells can be easily located by reconstructing the location from a plat map. Others, although not found specifically at the location noted on the plat map, are located closely enough that the well can be found. This is particularly true if the casing still extends above the surface or if equipment associated with the well is still visible at the site.

If, however, the casing has been cut off below ground or removed, locating the well is a more difficult task. Drilling practices, procedures and equipment have changed through time. However, one feature common to all drilling is the disturbance of the surface of the ground. The size, shape and evidence of the disturbance will vary from site to site and with time, but clues to well location can be found by noting the disturbance. Evidence of roads, clearings, drilling equipment layout, pits, pieces of equipment and vegetation changes can collectively indicate the approximate location of abandoned wells. Figures 9 and 10 show the two most common

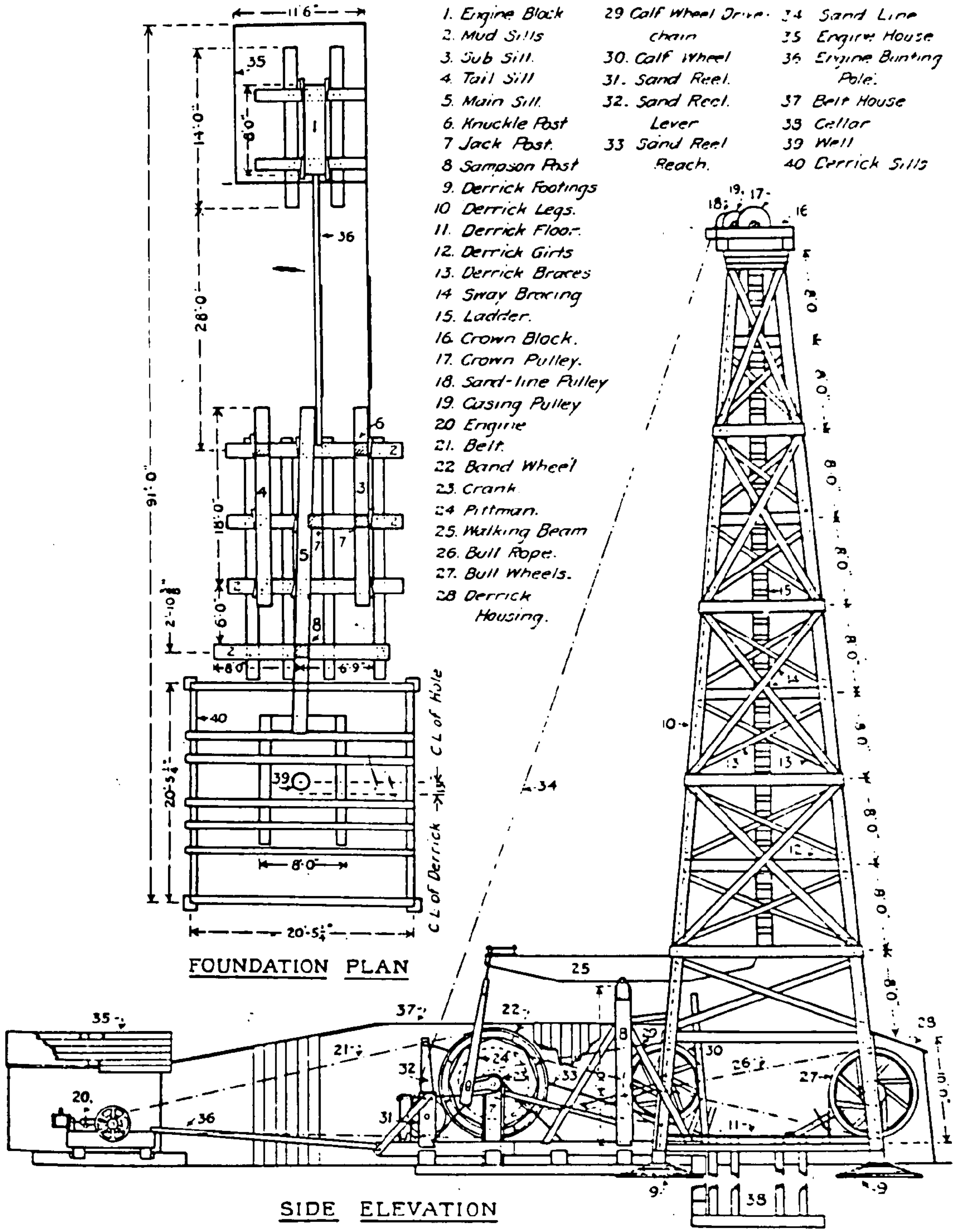


Figure 9. Plan and elevation of an 82-foot standard cable tool rig (Uren 1924).

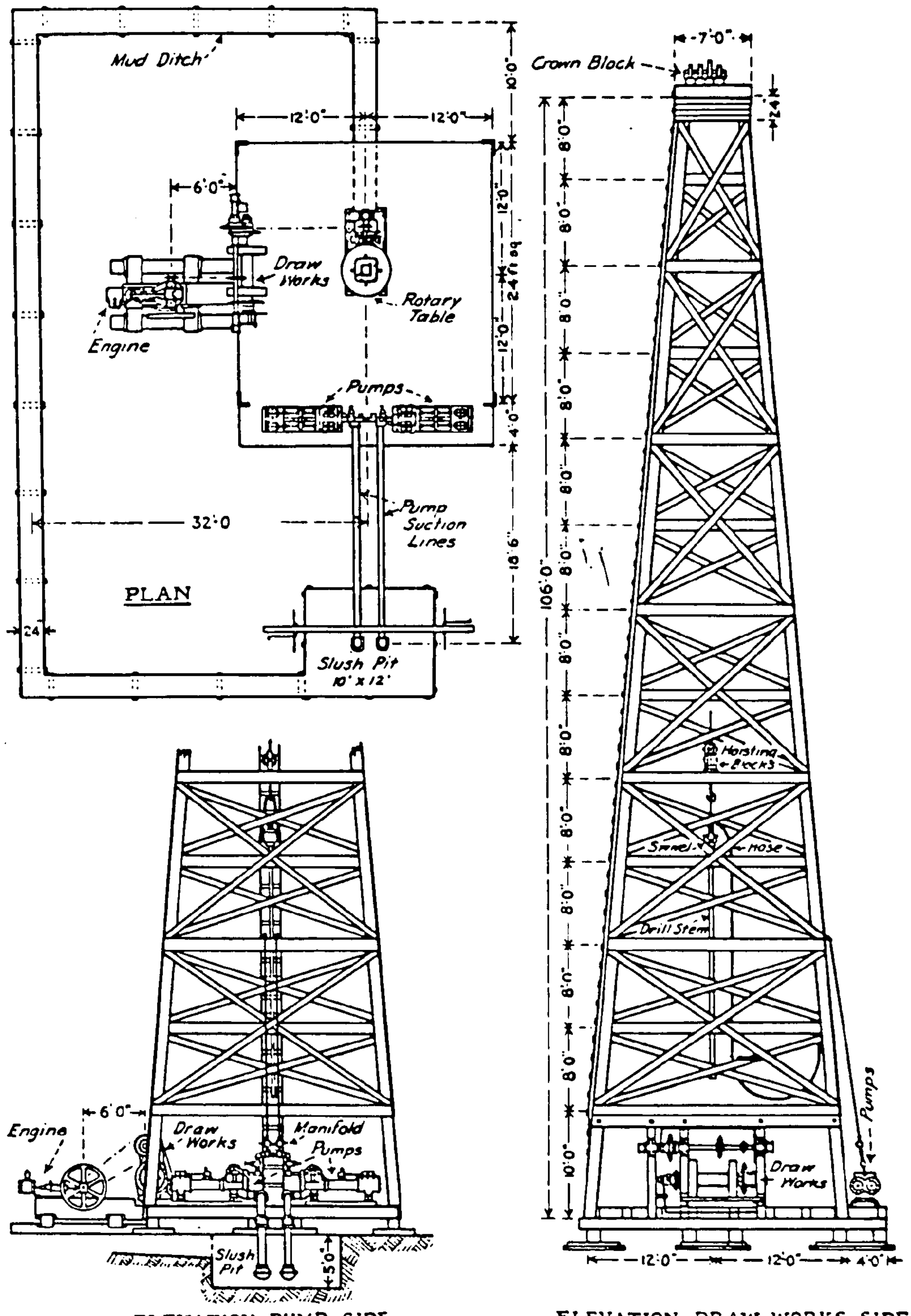


Figure 10. Plan and elevation of a 100-foot rotary rig (Uren 1924).

types of drilling equipment (cable tool and rotary) and typical equipment layouts which were used to drill oil and gas wells. The reader is referred to texts explaining common drilling practices at specified time intervals for more specific information (Brantly, 1971; Hager, 1921; Cloud, 1937; Uren, 1924, 1934 and 1946).

Field identification of well locations should begin by narrowing the search area as much as possible. If plat maps are available, reconstruction of the location by measuring from referenced property lines should be attempted. Often it may be necessary to try to locate reference points such as older property lines and bench marks from another source before actual measurement can begin. If plat locations are not available, then logical clues based on the information obtained from other sources should be used. Visual and logical clues may also be coupled with methods which use equipment to make identification and presence of certain objects easier. The remainder of the search relies on identifying evidence of drilling operations. Johnston et al. (1973) described in detail many items to look for when locating abandoned wells. Many of their field techniques are detailed in numbers 1-4 and 6-8 below:

1) Evidence of old roads that served well sites during drilling operations often is found through a study of aerial photographs. In the Appalachian regions and in hilly terrain, the roads were sometimes built above the well site, and the pipe and material were lowered down the side of a hill to the drilling rig.

2) A clue often found in the vicinity of the well is evidence of the water-supply and oil-storage tanks that were constructed during drilling and development. Often the location of these tanks is quite apparent because an area 15 to 20 or more feet in diameter was cleared and leveled for the tank base. The clearings or indentations made in the ground by the tanks are visible on aerial photographs, particularly in wooded areas where a difference in the growth in the trees can be detected. Tank markings such as indentations in the ground, pieces of redwood staves or pine plugs, and iron rods often indicate the location of a wooden tank. Clues indicating the location of steel tanks are nuts and bolts used in their construction and rusted pieces of metal fittings. Additional clues found in the area of an oil-storage tank are oil-saturated soil and a scarcity of vegetation. Unfortunately neither water nor oil-storage tanks were set at a uniform distance from the engine house or derrick floor. However, the oil-storage tank was usually set beyond and below the well so that gravity flow could be used, and the water tank was always set near the engine house. When either one or both of the tank locations are found, a search is made of the area between the tanks or in a 100-foot radius of a single tank for rig marks, such as indentations in the ground from rig foundation sills, pieces of metal from drilling and production operations, and indications of water and gas service pipelines.

3) Frequently in wooded areas, trees are found with pieces of wire line imbedded in their trunks, or with scars and deformities caused from their use as anchors for guy wires supporting the drilling rig. If three

or more scarred trees are found, the well may be located by triangulation; if only one or two trees are found, a search of the area must be made for additional clues.

4) An important clue often found in the vicinity of a well is the presence of large timbers or sills used in the construction of the derrick and engine house foundations. These timbers are about 18 inches square in cross section. The positions of the various sills and their distance from the well on an 82-foot standard cable-tool rig are shown in Figure 9. These distances will vary with the size of derrick required for drilling. In most cases, the only evidence of the sills are indentations made in the ground by the weight of the timbers. Occasionally, a few pieces of rotted wood are found.

5) Oftentimes concrete or brick foundations were erected to support derricks and power equipment. Four corner supports were laid or poured and a slab was offset to the side. Figure 11 shows the layout of a steam driven rotary rig of the 1930's. In most cases since the concrete is more resistant than timbers and more difficult to remove, the supporting structures are still evident (Figure 12).

6) During early development of the Appalachian areas, where many wells were drilled on the sides of steep hills or mountains, the standard cable tool rigs for convenience were faced in the same direction. In most cases, when looking from the engine house toward the front of the rig, the right-hand shoulder of the viewer was on the uphill side. This, locally known as a right-hand rig, placed the service road above and the bailer dump below the derrick. With this knowledge and evidence of the location of the engine house, water tank, or steam boiler, the probable location of the derrick floor, or possibly the actual wellbore may be found. If no evidence of the well is found, shovels, or in some areas bulldozers are used to find additional clues, such as spillways where sand and shale cuttings from the bailer have run down the hillside, or pits where the cuttings were collected and retained. Greener grass than surrounding area is evidence of spillways, or if salt water was bailed from the well, barren ground with no vegetation. Old pits usually are indicated by depressions or sink holes. Since the bailer is dumped on the downhill side, the derrick floor is above or uphill from the spillway or pit.

7) Another clue found in the vicinity of older wells is the presence of cinders or slag from the firebox of the steam boiler. However, there is no uniformity in the distance between the boilers and engine house, and a search of the area for additional clues is often needed.

8) In areas where land is under cultivation and no evidence of the well has been found, it often is useful to hire the farmer to plow his fields with furrows 16 inches or more in depth. Men follow the plow looking for evidence, such as sand and shale cuttings, rust-colored soil, or pieces of metal. Once enough clues have been located, excavation may be necessary to locate the well bore (refer to Excavation, Section 11).

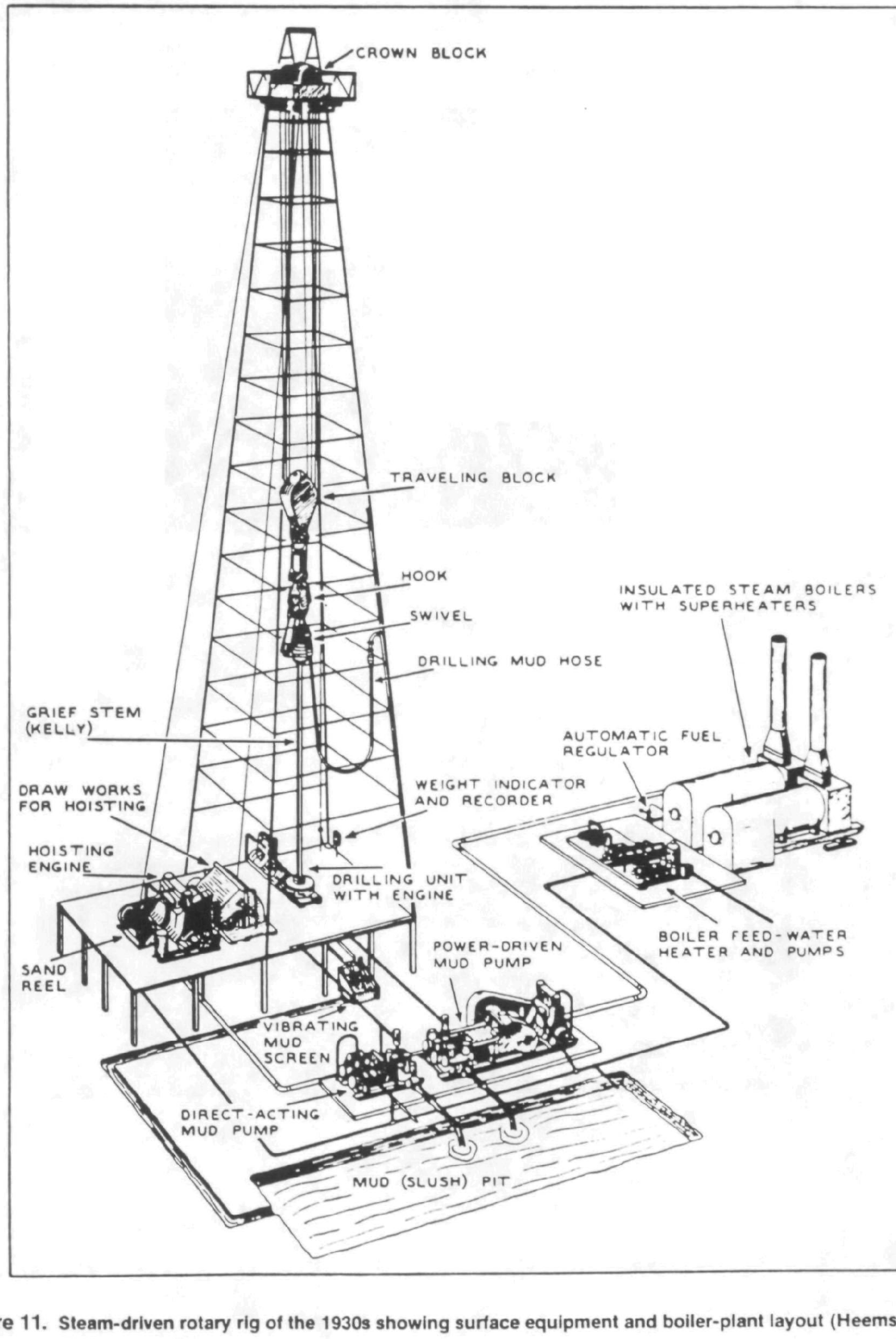
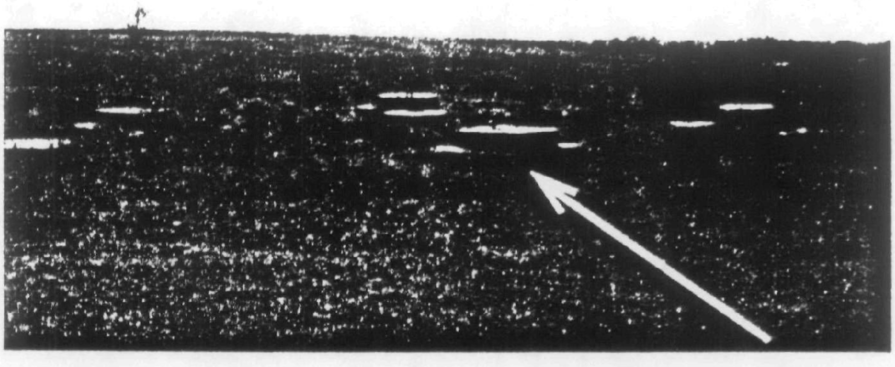


Figure 11. Steam-driven rotary rig of the 1930s showing surface equipment and boiler-plant layout (Heemstra et al. 1975).



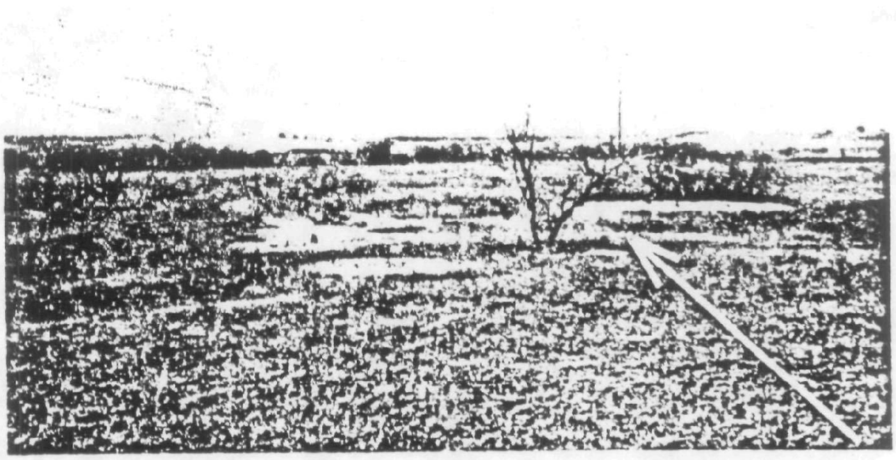


Figure 12. Surficial evidence of supporting structures around abandoned wells, Cleveland County, Oklahoma.

COST

The cost of using visual and logical clues is related to the amount of time spent compiling data from other methods and to the actual amount of time spent in the field. The manpower requirement and therefore the cost will vary according to the knowledge of the individual of drilling practices and the ability to recognize those expressions in the field. Since a visual/logical approach is often combined with other search methods, it may be difficult to separate the methods and specifically assign a cost.

ADVANTAGES AND DISADVANTAGES

Visual and logical methods are necessary when field location of a wellbore is required. There is no other method which replaces a field search. Familiarity with drilling practices and a "knack" for identifying these clues in the field enhances the chance of finding the desired well location. The use of selected pieces of field equipment may also increase the possibility of well location. However, the inherent disadvantage with the method remains that the well may not be found even when a labor intensive search is performed.

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SECTION 7

AERIAL PHOTOGRAPHIC INTERPRETATION

SYNOPSIS

Historical to present-day aerial photographs are available from many federal, state and local agencies as well as from private companies. While the scale and availability of aerial photographs vary with the date, location and original purpose of the photography, examination of the photographs at selected time intervals by a trained individual may provide information on oil and gas drilling and production activities. Coupled with knowledge of local drilling and production practices during certain time periods, well-drilling signatures can be developed to better define specific well locations.

DISCUSSION AND PROCEDURES

Aerial photographs or photographs taken from the air provide a detailed picture of the surface of the earth. Although aerial photographs were first recorded in the early 1850's, use of photographic coverage was not widely employed in the United States until the creation of the Agricultural Adjustment Administration [the present day Agricultural Stabilization and Conservation Service of the U.S. Department of Agriculture (ASCS)] in the 1930's (Avery, 1968). The art of identifying objects on those photos was not fully developed until World War II. Since that time, however, the majority of the United States has been photographed from the air at least once and often many times for various agencies of the federal government.

The scale of the photography has varied through time and with the original purpose of the photography for various agencies. Photography for the Soil Conservation Service (SCS) and ASCS has a scale of 1:20,000, while photography taken during the 1970's and 1980's has a 1:40,000 scale. Flights for the U.S. Geological Survey (USGS) are photographed at a scale of 1:24,000. NASA photography is available at a variety of scales ranging from 1:60,000 to 1:130,000 (K.K. Stout, personal communication, 1983).

Aerial photographs are taken by cameras mounted on an aircraft which flies in as straight a line as possible. The path of the aircraft as the photographs are taken is known as a flight line (Figure 13). Although the surface of the earth may be photographed at different angles resulting in a different perspective, most aerial photographs are taken by a camera aimed vertically at the earth's surface (Avery, 1968). A continuous series of photographs with 60 percent end lap and 30 percent side lap allows two

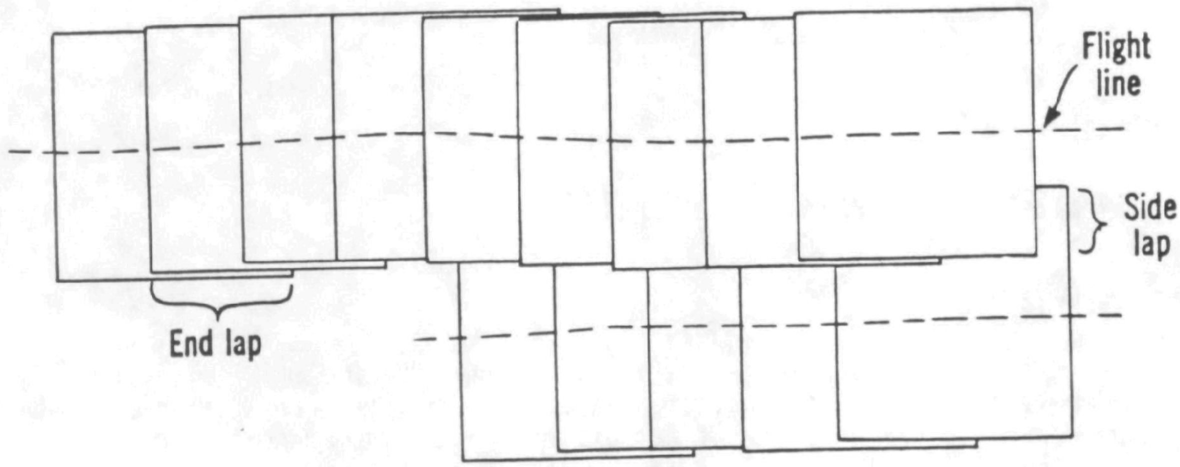

Figure 13. Parts of two flight strips of aerial photographs superimposed to show characteristic overlaps (Compton 1962).

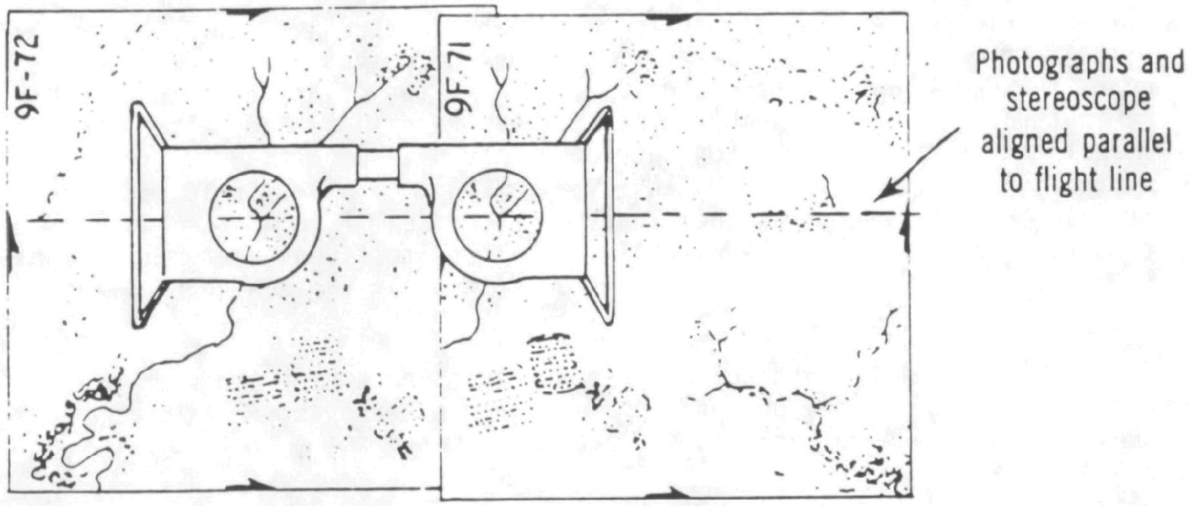

Figure 14. Position of pocket stereoscope relative to two photographs of a stereo pair (Compton 1962).

overlapping photographs in the direction of flight to be viewed with a stereoscope. Viewing the overlapping photographs through a stereoscope produces a three dimensional image (Figure 14) (Sabins, 1978). Aerial photographs are available either as contact prints or as transparencies which can be viewed with a light table for clearer definitions.

Examination of aerial photographs taken over time or at selected time intervals may provide better definition of specific well locations. These photographs can be used to supplement data obtained from a record search or to assist in field locating a well. The key to successfully examining aerial photographs lies in developing a "signature" for well drilling activities in the particular area. A signature is a combination of characteristics by which an object may be identified on a photograph (Sabins, 1978).

A signature for well drilling activities consists of noting applicable well construction and production features such as the construction of a derrick, anchoring for the derrick, a rig platform, the size and shape of brine pits, the source of power, brine disposal methods, roads for rig access, and other features both for the time period that the photograph was taken as well as for the past oil drilling and production techniques practiced in the area. A more detailed discussion of physical features associated with drilling activity is found in Section 6. Although the history of oil well drilling has been well documented (Brantly, 1971), drilling practices may vary from locale to locale depending on availability of natural resources, local preference and regulations. Therefore, familiarity with oil and gas drilling practices within the area is necessary for proper assessment of that area.

Once a signature has been developed for an area, aerial photographs may be chosen for years during which drilling and production activity actually took place (if recent enough) or for years which would exhibit post-drilling evidence. Historical photographs may show evidence of drilling and production activities which have since been obliterated from the surface.

The larger the scale of the aerial photograph, the easier it is to identify surface features. In general, imagery with a scale of 1:40,000 or larger may provide valuable information for the delineation of well locations to an accuracy within 20 to 30 feet. Imagery with a smaller scale may possibly be applicable, but delineation of the important smaller surface features may not be possible.

Aerial photographs of the United States are numerous and are available from a variety of sources. To assist in locating aerial photographs, the USGS National Cartographic Information Center (NCIC), 507 National Center, Reston, Virginia 22092, (703) 860-6045 maintains a computerized listing of available aerial coverage for the entire United States. The NCIC can provide a listing of all the aerial photographs available for the geographic area contained within a USGS 7 1/2 minute quadrangle map (Figures 15 & 16). The listing contains the agency or organization for whom the project was conducted, the date of the photography, the scale, the

*** NO4**		*** NO4**
NCIC	AERIAL PHOTOGRAPHY SUMMARY RECORD SYSTEM	DATE: 11/01/79
	INDEX CROSS REFERENCE	PAGE 58

AGENCY CODE	RPT TYP	O/M	SE CORNER LAT DEG	LAT MIN	LONG DEG	LONG MIN	FIPS CODE ST	CTY	DATE OF COVERAGE YR	MO	DAY	STA	AGENCY PROJECT CODE	IMAGE SCALE	FOCAL LENGT	FILM TYPE	FILM FMT	SENS CLAS	CLOUD COVER	CAM SPEC	QUAD COVER	REMARKS OR SCENE ID	FRAMES FROM	TO	CASSETTE NO.	FRAME
USGS	2	2	43	30	096	45			71	05	01	3	VCQX	32000	04	4	3	1	0	Y					0034	0520
NASAJS	3	2	43	30	096	45			70	11	05	3	1460	60997	06	2	3	2	0		3	614600030	0005	0013	0466	0738
NAS*JS	3	2	43	30	096	45			70	11	05	3	1460	114871	04	2	3	2	0		2	614600010	8785	8786	0466	0520
NASAJS	3	2	43	30	096	45			70	11	05	3	1460	112453	04	3	3	2	0		2	614600020	9088	9089	0466	0627
NASAJS	3	2	43	30	096	45			70	11	05	3	1460	114861	04	2	3	2	0			614600010	8787	8791	0466	0522
NASAJS	3	2	43	30	096	45			70	11	05	3	1460	113841	04	3	3	2	0			614600020	9090	9094	0466	0629
NASAJS	3	2	43	30	096	45			70	05	26	3	1290	117462	04	3	3	2	0		6	612900110	0053	0060	0442	0465
NASAJS	3	2	43	30	096	45			70	05	26	3	1290	62697	06	2	3	2	0		6	612900120	0082	0107	0442	0566
NASAJS	3	2	43	30	096	45			70	05	26	3	1290	115882	04	2	3	2	0		5	612900100	3960	3968	0442	0383
NASAJS	3	2	43	30	096	45			70	05	26	3	1290	115655	04	3	3	2	0			612900110	0040	0052	0442	0452
NASAJS	3	2	43	30	096	45			70	05	26	3	1290	126115	04	2	3	2	0			612900100	3954	3959	0442	0377
ASCS	1	2	43	30	096	45	46	099	68	07	07	3	VN	20000	05	4	3	1	0	Y		04				
ASCS	1	2	43	30	096	45	46	099	62	10	28	3	VN	20000	05	4	3	1	0	Y		04				
USGS	2	2	43	30	096	45			58	0"	07	3	VSS	16936	04	4	3	1	0	Y					0038	0108
ASCS	1	2	43	30	096	45	46	099	56	08	29	3	VN	20000	05	4	3	1	0	Y		04				
"SA	3	2	43	30	096	45			53	09	25	3	001	68799		4		1	0			1 320930843				
ASCS	1	2	43	30	096	45	46	099	51	08	27	3	VN	20000	05	4	3	1	0	Y		08				
ASCS	1	2	43	30	096	45	46	099	40	07	03	3	VN	20C00	05	4	3	1	0	Y		02				
NARS	1	2	43	30	096	45	46	099	38			3	VN	20000	05	4	3	1	0			ASCS PROJECT				
NASAJS	3	2	43	37	096	45			77	10	17	3	3690	115894	04	2	3	2	0		7	636900020	0033	0043	3691	0033
NASAJS	3	2	43	37	096	45			77	10	17	3	3690	116741	04	2	3	2	0		3	636900020	0072	0081	3691	0072
NASAAM	3	2	43	37	096	45			76	07	23	3	02392	126000	04	2	3	2	1		2	576002392	4500	4502	0243	0667
NASAAM	3	2	43	37	U96	45			76	07	23	3	02392	127000	04	2	3	2	1		2	576002392	4503	4503	0243	0670
NASAAM	3	2	43	37	096	45			76	07	23	3	02392	125000	04	2	3	2	2		2	576002392	4504	4505	0243	0671
ASCS	1	2	43	37	096	45	46	099	76	05	11	3		40000	04	4	3	1	0	Y		06				
USGS	2	2	43	37	096	45			76	05	11	3	VEDD	36000	04	4	3	1	0	Y					0055	0681
NASAAM	3	2	43	37	096	45			75	05	16	3	02077	129000	04	2	3	2	0		3	575002077	2770	2770	0399	0432
NASAAM	3	2	43	37	096	45			75	05	16	3	02078	129000	04	3	3	2	0		3	575002078	1819	1819	0399	0318
NASAAM	3	2	43	37	096	45			75	05	15	3	02075	124000	04	2	3	2	0		8	575002075	2611	2613	0399	0170
NASAAM	3	2	43	37	096	45			75	05	15	3	02076	124000	04	3	3	2	0		8	575002076	1660	1662	0399	0605
NASAAM	3	2	43	37	096	45			75	05	15	3	02075	131000	04	2	3	2	0			575002075	2616	2626	0399	0173
NASAAM	3	2	43	37	096	45			75	05	15	3	02076	131000	04	3	3	2	0			575002076	1663	1675	0399	0608
USGS	2	2	43	37	096	45			71	05	00	3	VCQX	32000	04	4	3	1	0	Y					0034	0526
NASAJS	3	2	43	37	096	45			70	11	05	3	1460	60997	06	2	3	2	0		5	614600030	0005	0013	0466	0738
NASAJS	3	2	43	37	096	45			70	11	05	3	1460	113841	04	3	3	2	0			614600020	9090	9094	0466	0629
NASAJS	3	2	43	37	096	45			70	11	05	3	1460	114861	04	2	3	2	0			614600010	8787	8791	0466	0522
NASAJS	3	2	43	37	096	45			70	05	26	3	1290	117462	04	3	3	2	0		6	612900110	0053	0060	0442	0465
NASAJS	3	2	43	37	096	45			70	C5	26	3	1290	62697	06	2	3	2	0		6	612900120	0082	0107	0442	0566
NASAJS	3	2	43	37	096	45			70	05	26	3	1290	115882	04	2	3	2	0		5	612900100	3960	3968	0442	0383
NASAJS	3	2	43	37	096	45			70	05	26	3	1290	63891	06	2	3	2	0		2	612900120	0108	0113	0442	0592
NASAJS	3	2	·3	37	096	45			70	05	26	3	1290	123625	U4	2	3	2	0		2	612900100	3983	3989	0442	0406
NPSAJS	3	2	43	37	096	45			70	05	26	3	1290	119655	04	3	3	2	0			612900110	0040	0052	0442	0452

Enlarged summary record frame

Figure 15. Aerial photography summary record from the National Cartographic Information Center.

Agency Code
All contributors are listed alphabetically by an agency code

Rpt Typ (Report Type)
1 = county format
2 = 7 5-minute quad format
3 = four-corner format

Q/W (Quadrant of the World)
1 = northeast
2 = northwest

SE Corner, Lat/Log—Deg/Min
Degree and minute of latitude and longitude of southeast corner of 7 5-minute quadrangle Information listed in increasing degrees of longitude

FIPS Code, State/County
Assigned State and county numbers using Federal Information Processing Standards publication codes

Date of Coverage, Yr/Mo/Day
Year month, and day photography flown Date also reflects estimated time of completion for planned projects

Sta (Status)
1 = photography planned
3 = photography completed

Agency Project Code
An agency's project identification

Image Scale
Scale of photographs expressed as a whole number (some scales were derived using flight height and camera focal length)

Focal Lengt (Focal Length)
01 = 1 75 in or 44 mm
02 = 3 in or 76 mm
03 = 3 46 in or 88 mm
04 = 6 in or 152 mm
05 = 8 25 in or 210 mm
06 = 12 in or 305 mm
07 = 24 in or 610 mm
08 = 3 96 in or 101 mm
09 = 9 430 in or 240 mm
10 = 6 738 in or 171 mm
11 = 3 35 in or 206 mm
20 = other

Film Type (Emulsion)
1 = black and white infrared
2 = color infrared
3 = color
4 = black and white
5 = thermal
9 = other

Film Fmt (Film Format)
1 = 2 76 in × 2 76 in or 70 mm × 70 mm
2 = 4 5 in × 4 5 in or 11 cm × 11 cm
3 = 9 in × 9 in or 23 cm × 23 cm
4 = 9 in × 18 in or 23 cm × 46 cm
5 = 7 in × 7 in or 18 cm × 18 cm
6 = 7 in × 9 in or 18 cm × 23 cm
7 = 6 in × 8 in or 15 cm × 20 cm
9 = other

Sens Clas (Sensor Class)
1 = vertical carto (implies stereo)
2 = vertical reconnaissance
3 = side-looking airborne radar
4 = oblique
9 = other

Cloud Cover (Percentage of)
0 = 0% 5 = 50%
1 = 10% 6 = 60%
2 = 20% 7 = 70%
3 = 30% 8 = 80%
4 = 40% 9 = 90%

Cam Spec (Camera Specifications)
Indicates if camera meets calibration specifications
Y = Yes N = No Blank = Unknown

Quad Cover (Quadrangle Coverage)
1 = 10% 6 = 60%
2 = 20% 7 = 70%
3 = 30% 8 = 80%
4 = 40% 9 = 90%
5 = 50% 0 or blank = 100%

Remarks
This is a dual-purpose field The heading REMARKS refers usually to free-form data entered by agencies other than NASA For example, the USFS frequently enters the name of a national forest The USGS usually enters "QUAD-CENTERED" on planned and in-progress photographs and a microfilm identification on completed photographs The subheadings

Scene	Frames		Cassette	
ID	From	To	No	Frame

are aligned with entries for NASA data only, and identify the actual photographic frame range containing the quadrangle coverage and the microfilm cassette locator information for previewing the photographs

Figure 16. Explanation of symbols and codes on aerial photography summary.

conditions (such as cloud cover) under which the photography was taken, the photographic techniques used and who now holds the film. With this information, it is possible to order copies from the holder of the photographs since all photographs listed are available for public purchase.

The photographic information is filed by the latitude and longitude of the southeast corner of a USGS 7 1/2 minute quadrangle map (such as a topographic map). Topographic index maps for each state are available free of charge by contacting USGS, 1200 S. Eads Street, Arlington, Virginia 22202, (703) 557-2751. Topographic maps for states east of the Mississippi River are available from the Arlington, Virginia office and other selected outlets at a cost of $2.00 each. Maps for states west of the Mississippi are available from approved distribution centers and from USGS, Box 25286, Denver Federal Center, Denver, Colorado 80235, (303) 234-3832.

In addition to the listing obtained from NCIC, recent photo index sheets, index mosaics and photography flown for the SCS or ASCS, are usually available for examination at local offices. These recent photographs can then be ordered from the appropriate source if they prove helpful.

Other sources of aerial photographs may be selected state agencies, some highway departments, various local entities and private corporations. Private aerial survey companies may have a large holding of photographs which may be available. The scale and angle at which the imagery was photographed should be checked before ordering any photographs.

COST

The cost of aerial photographic interpretation is related to the number of photographs which need to be purchased and the manpower requirement necessary to interpret the photographs. The size of the study area, the scale of photography and the familiarity and expertise of the individual performing the interpretation will also influence the cost. Material requirements are relatively small. Printouts from NCIC average $2.00 per 7 1/2 minute quadrangle. Topographic index maps are available free of charge and USGS 7 1/2 minute quadrangle topographic maps are available for $2.00 each. Aerial photography from government sources ranges in price depending on the type of photography (transparencies or prints) and the size of the reproduction. Typical charges are listed in Table 3 for single reproductions. Stereo coverage necessitates the purchase of more than one reproduction for each area to be reviewed.

Table 3. TYPICAL COSTS FOR STANDARD AERIAL PHOTOGRAPHY AVAILABLE FROM THE U.S. GOVERNMENT

	Aircraft Data	
Image Size	**Product Material**	**Black & White Unit Price**
22 9 cm (9 0 in)	Paper	$ 5 00
22 9 cm (9 0 in)	Film Positive	8 00
22 9 cm (9 0 in)	Film Negative	12 00
45 7 cm (18 0 in)	Paper	20 00
68 6 cm (27 0 in)	Paper	25 00
91 4 cm (36 0 in)	Paper	35 00
55 8 mm (2 2 in)	Film Positive	8 00
55 8 mm (2 2 in)	Film Negative	10 00
11 4 cm (4 5 in)	Film Positive	8 00
11 4 cm (4 5 in)	Film Negative	10 00
22 9 x 45 7 cm (9 x 18 in)	Paper	12 00
22 9 x 45 7 cm (9 x 18 in)	Film Positive	16 00
22 9 x 45 7 cm (9 x 18 in)	Film Negative	20 00

Manpower requirements will vary depending on the familiarity of the individual with both the drilling practices in the area and the interpretation of aerial photographs. Cursory reviews can often be performed by lay people using pocket stereoscopes and contact prints. However, an experienced interpreter is necessary to correctly and thoroughly analyze the photography. Professional aerial photographic interpretation companies are also able to provide interpretation of photographs when identification of drilling and production activity and well locations are needed. Since these individuals are specifically trained to look for man-made disturbances, they can often find disturbances that an untrained eye would miss. Professional services are available on a time and materials basis. Typical charges for time would range from $20 to $60 per hour depending on whether the company searched for and located the photographs or only interpreted photographs which were provided. After development of a signature for the area, a stereo pair of photographs could typically be reviewed in one half to one hour. Material costs for photographs would normally be an additional expenditure.

ADVANTAGES AND DISADVANTAGES

Aerial photographs may be used to help locate surface expressions of abandoned wells or associated drilling and production activities. These features may or may not be evident on the surface. Historical photographs may actually show drilling and production activities or evidence of activities which have since been obliterated at the surface. The photography may be readily available at a low cost. However, the disadvantages are that photography may not be available for a particular area and that even when the suspected location of a well has been found on the photography, the location of the well must still be verified. Additionally, the interpretation of aerial photographs requires the eye of a trained individual to discern subtle features.

CASE STUDIES

Drilling activity was widespread in Osage County, Oklahoma during the 1930's. To help determine the applicability of aerial photographs in pinpointing well locations a study is currently being conducted in selected areas by the EPA. Figure 17 shows an aerial photograph in which drilling derricks are easily identified. Figure 18 depicts an area in which drilling activities had taken place in the past. Identification of drilling sites was possible by a signature developed for this particular area. One local production technique in this area during the 1930's was the construction of a central powerhouse from which lines were run to each well. These linear features are evident, but their association with oil and gas drilling would be difficult if local production practices were unknown. A complete assessment of the use of historic aerial photographs in determining well locations is currently underway (K.K. Stout, personal communication, 1983).

Figure 17. Aerial photograph showing derricks, Osage County, Oklahoma, 1937.

Figure 18. Aerial photograph showing central power house, rod lines to the power house and brine pits, Osage County, Oklahoma, 1937.

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SECTION 8

METAL DETECTORS

SYNOPSIS

Metal detectors are a tool which can be used in intensive field searches to locate abandoned wells. Metal detectors detect shallow buried metallic objects and thus, they can be used to identify the actual location of metal casings or other metal objects associated with drilling and production practices. The distribution of these metal objects may lead to an implied well location even if no metallic casing is present. Some metal detectors are inexpensive pieces of equipment which require a minimum of knowledge to either operate or interpret the output. They can be operated by one person and are suitable for most terrain and vegetative cover. The cost of conducting a search with a metal detector may be significantly lower than when other pieces of equipment are used to intensively search an area.

DISCUSSION AND PROCEDURES

Metal detectors are designed to locate buried metallic objects. A metal detector is sensitive to ferrous metals such as iron and steel and non-ferrous metals such as aluminum, brass, and copper. Metal detectors are commonly used to locate buried pipelines, survey markers and manhole covers and to search for buried treasure.

The metal detector is designed to continuously scan an area for metallic objects. The basic principle of operation of a metal detector relies on the induction of an electromagnetic field around an object by a transmitter (Yaffe et al., 1981). A coil within the instrument is arranged and adjusted such that the eddy currents from a nearby metallic source disturb the electromagnetic balance of the instrument (Evans, 1982). This imbalance creates an electrical signal that can be detected by the user. The signal is usually manifested as both a meter deflection and an audible tone which can be adjusted to override background noise or can be heard through a set of headphones.

The response of the metal detector to metallic objects depends on the size, shape, orientation, composition and distance of the object from the detector as well as the sensitivity of the equipment (Evans, 1982). In general, the larger and closer the object, the stronger the signal. Some metal detectors have adjustments so that the sensitivity of the equipment can selectively "concentrate" on larger, smaller or deeper objects depending on the desired scope of the search. Metallic objects buried within 5 feet of the ground surface can typically be detected. However, under some circumstances, large metallic objects which are located as deep as 10 feet below the surface can be detected.

A metal detector is a portable piece of equipment which is operated by one invidividual. Two representative types are illustrated in Figure 19. The equipment is suitable for searches in all types of terrain and vegetation.

Metal detectors may be employed in field reconnaissance efforts to locate metallic casing and buried metal objects associated with well drilling and production activities. As outlined in the Section 6, many metallic objects associated with drilling and production activities may have been discarded or left at the site. The distribution of these objects may help to narrow the search area, may help identify the location of the casing, or may help an individual infer the location of the well even when no metallic casing is present.

A search with a metal detector is conducted by walking over the desired area and operating the equipment in a sweeping motion. Since the equipment operates in a continuous mode, the equipment will respond to any metal encountered in that sweep. The most effective way to conduct a search is to establish a grid pattern of the area to be searched. The grid pattern can easily be amended if the scope or area of the search needs to be altered. This provides a systematic approach to evaluating the area and helps to insure that if a casing is present, it is not overlooked. When signals from the equipment indicate the presence of a metal object, the location should be marked with a wooden stake for later reference or the object uncovered immediately. Marking the location with a wooden stake rather than a metal stake prevents interference with the operation of the equipment. Marking the locations of the metal objects also provides visualization of the distribution of metal objects around the area. This distribution may help an individual to infer the location of the well even when no metallic casing is found.

COST

The cost of conducting a survey with a metal detector is dependant on the cost of the equipment and the manpower necessary to conduct the search. Metal detectors suitable for conducting a search for abandoned wells are available for purchase at prices ranging from $225 to $400. Additional accessories to provide for more convenient equipment operation or storage may slightly increase the cost.

Manpower requirements will vary depending on the familiarity of the individual with the local drilling and production activities, the size of the area to be searched, the familiarity of the individual with use of the equipment and the success in quickly locating the abandoned well. The ease of operation and self explanatory output of signals by a metal detector allow an individual to successfully operate a metal detector with a minimum

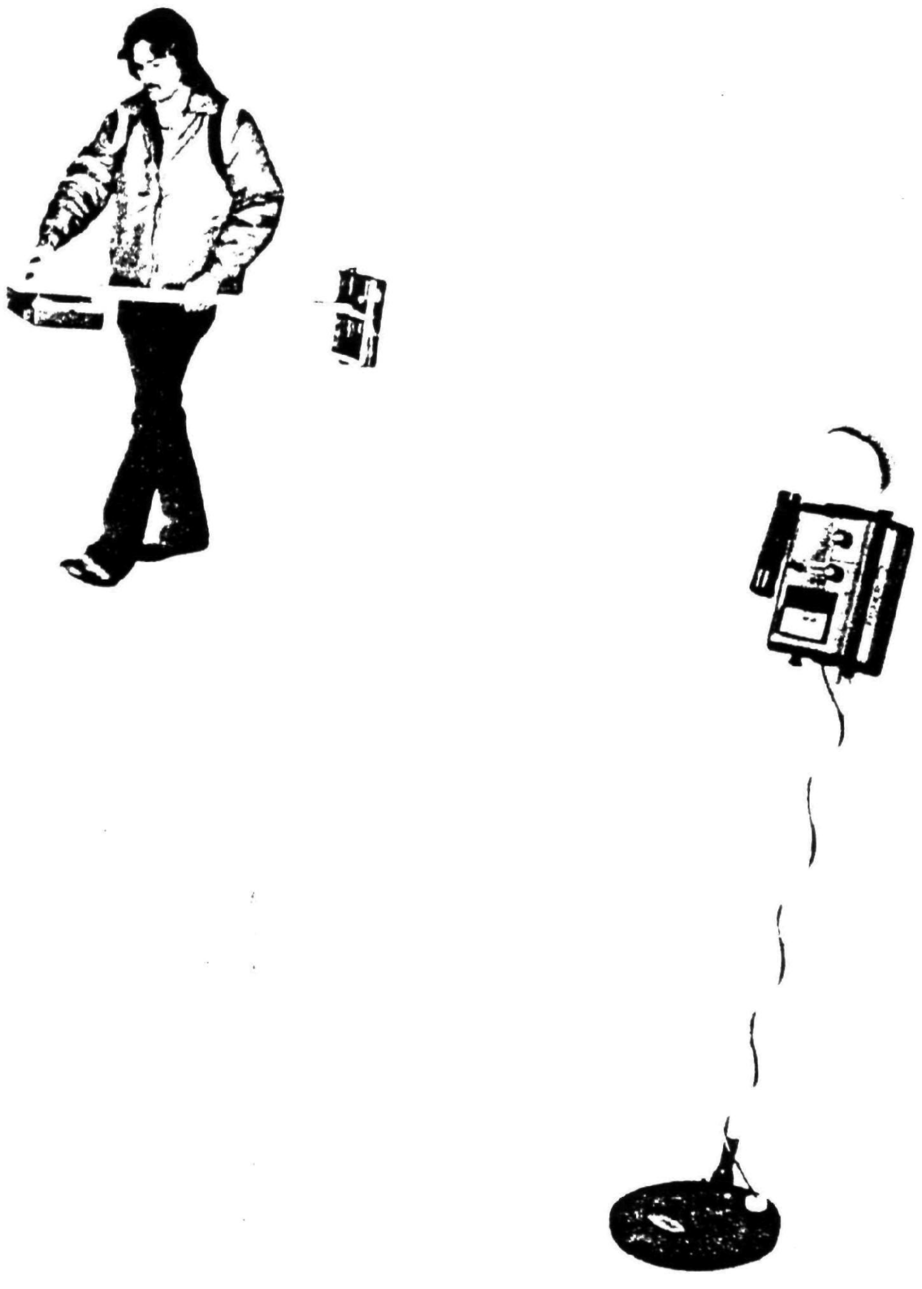

Figure 19. Metal detectors (Fisher M-Scope product literature).

of training. Familiarity with the equipment will allow the individual to quickly identify meaningful equipment responses from background noise, thereby reducing the amount of time necessary for the search. Because of the relative ease in operation of the equipment and interpretation of the results, the expense for individuals or companies with specialized training may not be necessary. Manpower requirements may still be relatively large because of the time involved in conducting the survey. Uncovering the detected objects may also require a substantial amount of time after the search has been conducted.

ADVANTAGES AND DISADVANTAGES

Metal detectors can be used to help identify the location of metal casings and metal objects associated with drilling and production activities. The equipment is relatively inexpensive and can be operated by an individual with limited training on the instrument. The metal detector emits signals which are easy to interpret and require no post-field-work analysis. Operation of the equipment is performed by one individual and the equipment is portable and suitable for all types of terrain and vegetative cover.

Metal detectors are limited to finding metallic objects which are buried at shallow depths. Therefore, if the well does not contain casing, if the casing is at a greater depth than the limit of the instrument or if the casing is non-metallic, the metal detector cannot be used to specifically locate the abandoned well. In these cases, however, the distribution of any other metal objects associated with drilling and production activities may help an individual to infer the location of the well. The area to be searched by methods such as excavation may thereby be narrowed.

CASE HISTORY

A study conducted by the U.S. Bureau of Mines sought to determine the location of abandoned wells by field searches with electromagnetic metal detectors (Johnston et al., 1973). Attempts were made to locate wells in both the Appalachian region and in the Midcontinent area using a variety of metal detectors. The status and general location of the wells were determined prior to the beginning of the field search. The metal detectors were successful in locating the casing and many metal objects associated with drilling and production activities (Figure 20). The distribution of the metal objects were plotted to determine radial distribution around known and unknown well sites (Figure 21). The report cited systemmatic field searches by metal detectors as a viable method of determining the location of abandoned wells.

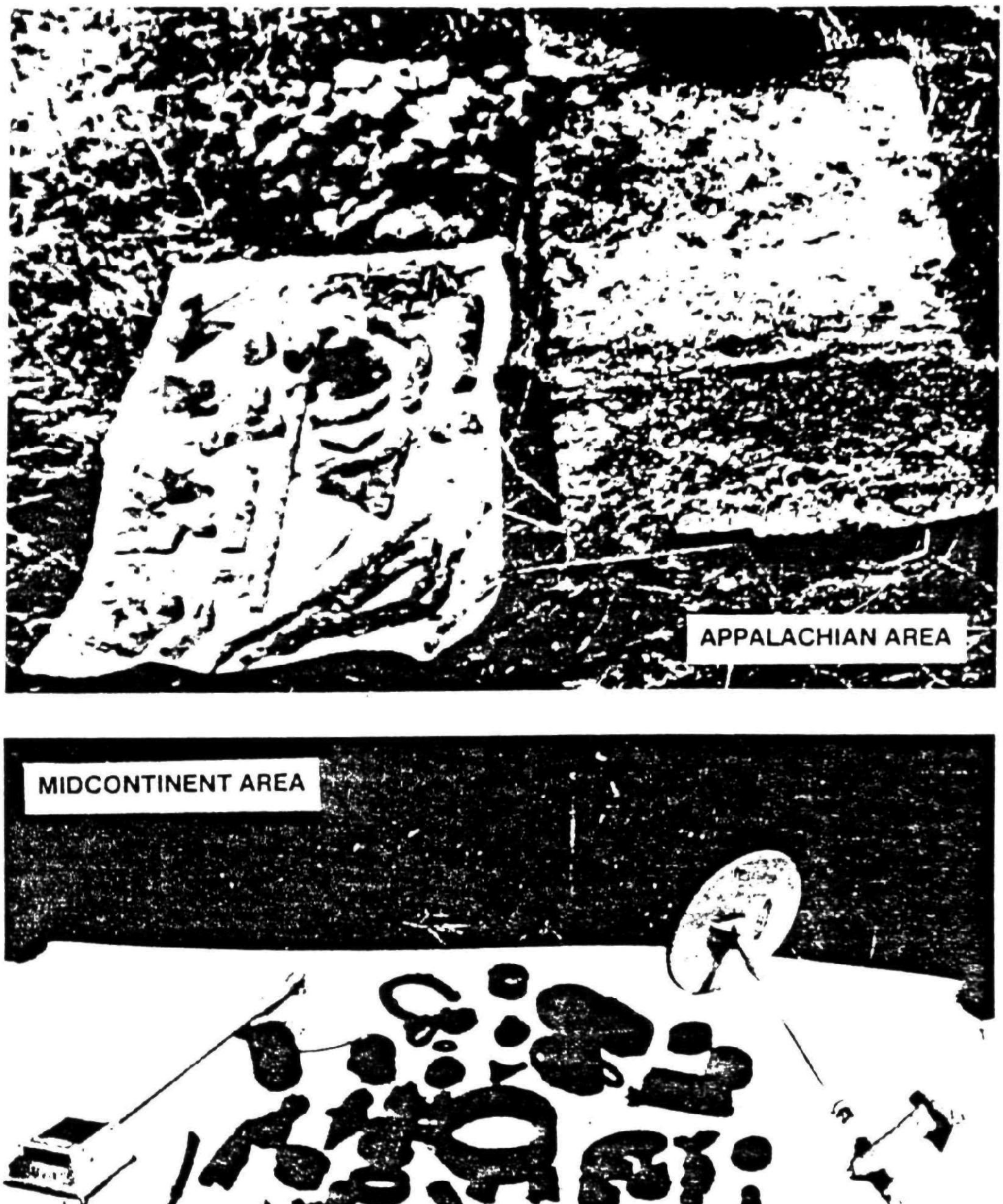

Figure 20. Metallic evidence uncovered in the vicinity of abandoned well, Appalachian area and Midcontinent area (Johnston et al. 1973).

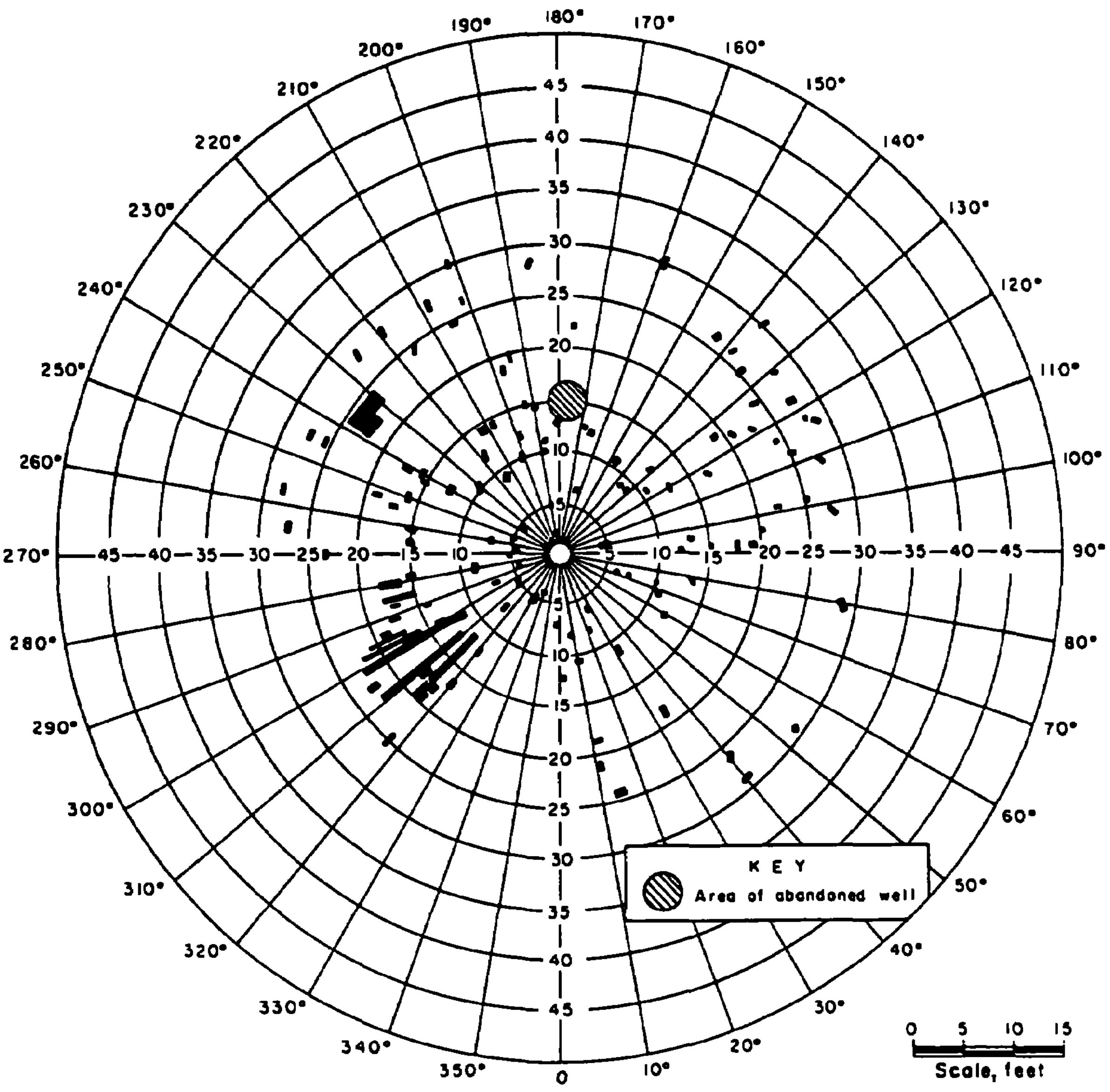

Figure 21. Location of metallic objects excavated from the area around abandoned well, Appalachian area (Johnston et al. 1973).

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SECTION 9

MAGNETOMETERS

SYNOPSIS

Magnetometers respond to changes in the magnetic field of the earth produced by ferrous metal materials on and within the earth. Ground-based magnetometer searches can be used to determine the location of metal well casings and ferrous objects associated with well drilling and production practices. Aerial magnetometer surveys provide a rapid reconnaisance method to detect the presence of metallic casings. This information can then be used in combination with other ground-based search techniques. Subsurface magnetometers may help to determine the depth of casing in an abandoned well. Portable magnetometers used in ground-based searches are suitable for most types of terrain and vegetative cover and range in price from relatively inexpensive to moderately expensive. Expertise requirements for operation of the portable equipment may range from low to moderate depending on the sophistication of the equipment selected. Professional surveys using magnetometers may also be available. Aerial surveys are considerably more expensive than ground-based magnetometer searches, require professional data interpretation and require ground verification of magnetic anomalies. Subsurface surveys are also expensive and have limited application for determining the location of abandoned wells.

DISCUSSION AND PROCEDURES

Magnetometers measure changes in the magnetic field of the earth (Koerner et al., 1982). The magnetic field of the earth resembles the field of a bar magnet located at the center of the earth with the poles of the magnet oriented north-south (Breiner, 1973). The magnetic properties of the rocks and soil of the earth are related to their percent composition of ferrous material. The magnetometer detects only ferrous material by responding to the magnetic intensity of the material. The ferrous material may either be naturally occuring earth materials or man made ferrous objects. Traditional applications of magnetometers include: 1) location of buried objects such as pipelines, well casing, drums in landfills and other metal objects, 2) mineral exploration, 3) geologic mapping, 4) engineering geology and 5) archaeology.

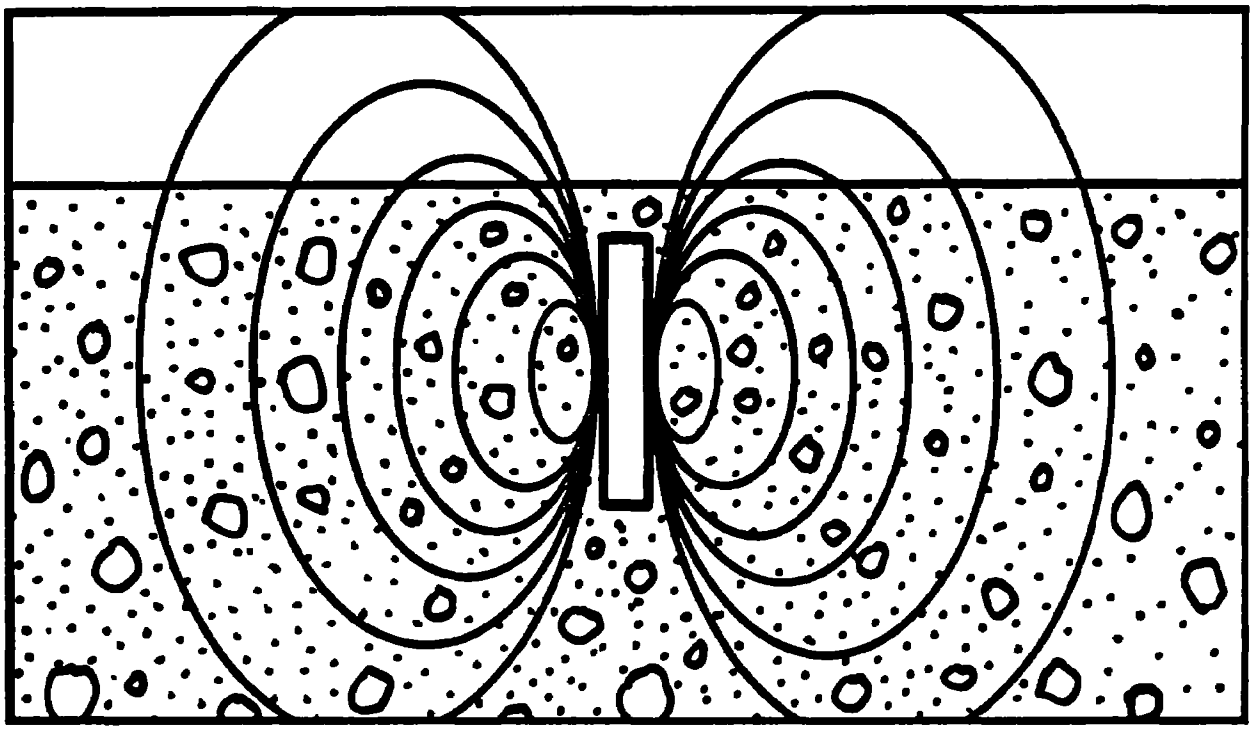
Magnetometers can be used for surface, airborne, and borehole reconnaissance. These applications may be useful either in combination with one another or with other methods suggested in this report. An airborne magnetometer may be used when general reconnaissance of an area is desired. A surface survey may be desired to pinpoint the location of wells which contain casing. When the casing is at depth, a borehole technique may be necessary to locate the top of the casing.

A variety of different types of magnetometers are employed in these applications. Fluxgate, proton, and optically pumped vapor magnetometers are the most widely available (Nettleton, 1976). Fluxgate magnetometers provide a continuous scan of an area. Proton or optically pumped vapor magnetometers provide discrete values at selected locations. The output of the instrument may be an audible tone, a numeric display or a continuous strip chart depending on the instrument selected.

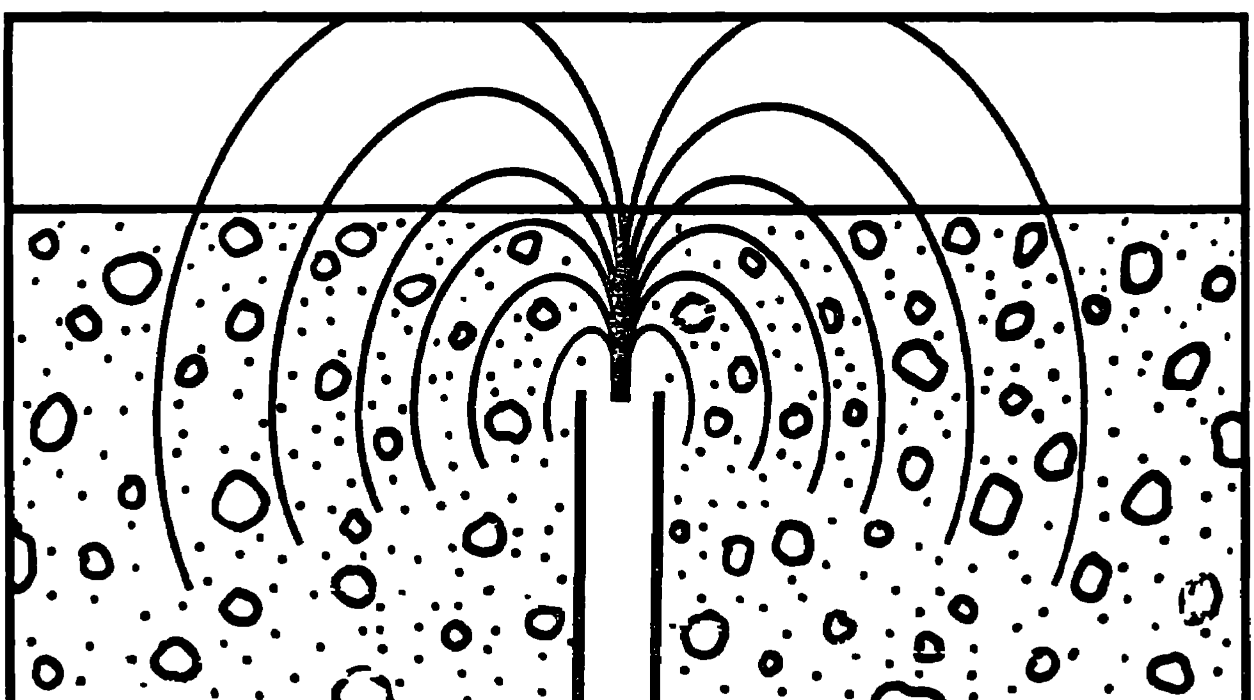
Although all magnetometers respond to changes in the magnetic field of the earth, each type of instrument employs a slightly different mode of sensing. In a fluxgate magnetometer, a saturated magnetic field is established around a small iron core by passing an alternating current through the coil. This magnetic field undergoes changes in the saturation level in response to variations in the magnetic field of the earth (Benson et al., 1983). The changes are subsequently amplified and displayed as an output on the magnetometer (Griffiths and King, 1965). In a proton magnetometer, an excitation voltage is applied to a coil which surrounds a small container of liquid (Benson, et al., 1983). This voltage induces a polarizing field within the magnetometer which results in the protons "lining up" along the axis of the induced field. When the field is removed, the spinning protons precess to realign themselves along the axis of the earth's field. The precession frequency is proportional to the magnitude of the earth's field (Nettleton, 1976). The frequency is measured and translated into a measurement of the absolute magnetic field of the earth. An optically pumped vapor magnetometer uses electrons rather than protons to "line up" in the earth's magnetic field when stimulated. These instruments most commonly employ cesium, rubidium or metastable helium to measure the magnetic field (Nettleton, 1976).

The response of the magnetometer to a buried metal object is dependent on the object's 1) mass, 2) geometry, 3) orientation magnitude and direction of the permanent magnetization and 4) distance from the magnetometer (Evans, 1982). The single most important factor is the distance of the object from the magnetometer (Breiner, 1973). The geometry of the object is also important. The signal will be stronger if the object has a longer length-to-diameter ratio and if the object is oriented perpendicular to the surface of the ground (Figure 22).

The response of the magnetometer may be affected by the presence of man-made features such as fences, power lines, reinforcing steel in concrete, pipelines and buildings. In addition, fluctuations within the earth's own magnetic field due to diurnal changes or magnetic storms will affect the readings obtained by a magnetometer (Breiner, 1973). Changes in the magnetic field of the earth are important when taking detailed measurements.



METAL OBJECT



WELL CASING

Figure 22. Diagram showing magnetic field surrounding well casing and metal object (modified from Schonstedt Instrument Co. product literature).

Magnetometers can be effectively used to search for metal casings of abandoned wells because of their long length-to-diameter ratio, their vertical orientation and their ferrous metal composition. The magnetometer can be used in ground, air or subsurface applications. Each of these is discussed in more detail below.

Ground searches for either metal casings or pieces of metal associated with well drilling and production activities can be accomplished by using portable magnetometers such as those shown in Figure 23. The equipment can be operated by one individual and is suitable for use in all types of terrain and vegetative cover. A ground search with a magnetometer is conducted by walking over the desired area in an established grid pattern. The grid spacing can be adjusted according to the desired results and the sensitivity of the equipment. Continuous scanning equipment is operated by sweeping the magnetometer in an arc as the site is traversed. Magnetometers which provide discrete digital readouts are operated by holding the sensor stationary and taking readings at regular intervals. The reading and reference location should then be recorded either in writing or internally within instruments having memory capabilities. Locations where the magnetometer registered either an audible sign or higher numeric value indicate the possible presence of a ferrous object. These locations should be marked with wooden stakes as the survey proceeds. Truck-mounted equipment is also available, but may not be applicable for small search areas.

Numerical readouts from magnetometers can be plotted along a traverse line to show the effect of a buried casing on readings obtained with a magnetometer (Figure 24). The shape of the curve produced by the object will generally be broader if the object is located at greater depth below the ground surface. The curve may be asymmetrical if the object is not parallel to the induced magnetic field (Breiner, 1973). Figure 25 illustrates different shapes of curves and their relationship to the object. Interpretation of the results from magnetometers requires familiarity with the equipment as well as an ability to interpret the data. Magnetometers with continuous scanning capabilities and only audible signals require less expertise to operate and require no further interpretation of the data.

Airborne magnetometer searches are conducted by mounting a magnetometer in an airplane or on a "bird" which is suspended from an airplane or helicopter (Figure 26). The aircraft is flown in a prescribed flight pattern with the spacings of the lines and height of the aircraft determined by the emphasis of the survey. The most widespread use of aerial magnetometer surveys is in mineral exploration where flight lines are normally one to two miles wide at heights of approximately 1000 feet above the surface (Nettleton, 1976). The flight pattern of the aircraft is referenced to the ground by aerial photography taken from the aircraft at the time of the magnetometer survey or by flying the aircraft in a known relationship with ground-based transponders (Nettleton, 1976). The results obtained from the survey must be adjusted to eliminate unwanted sources of magnetic variation and the data must be interpreted.

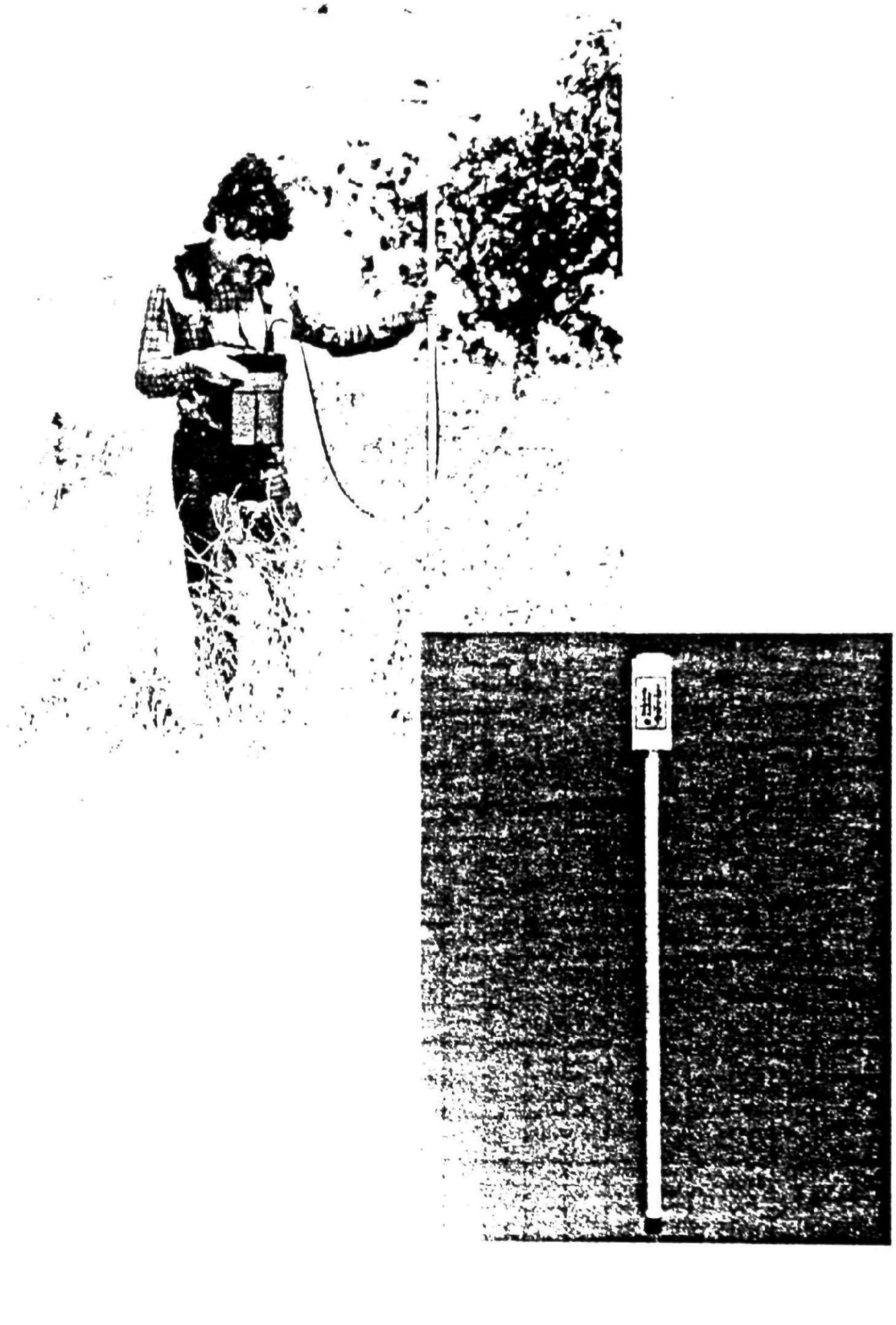


Figure 23. Different types of portable magnetometers (EG&G Geometrics product literature and Schonstedt Instrument Co. product literature).

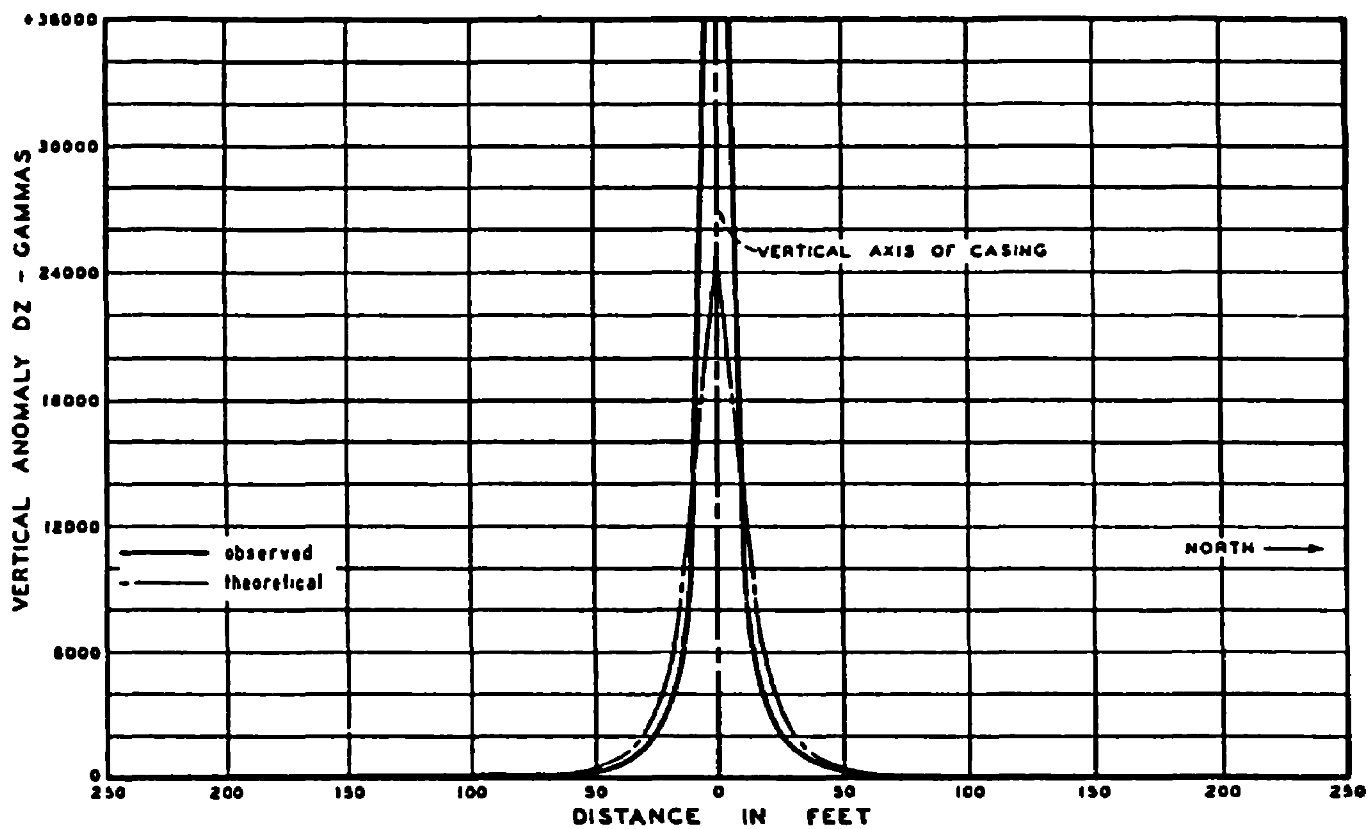


Figure 24. Comparison of observed and theoretical anomaly produced by a 4,609 foot vertical string of casing (Barret 1931).

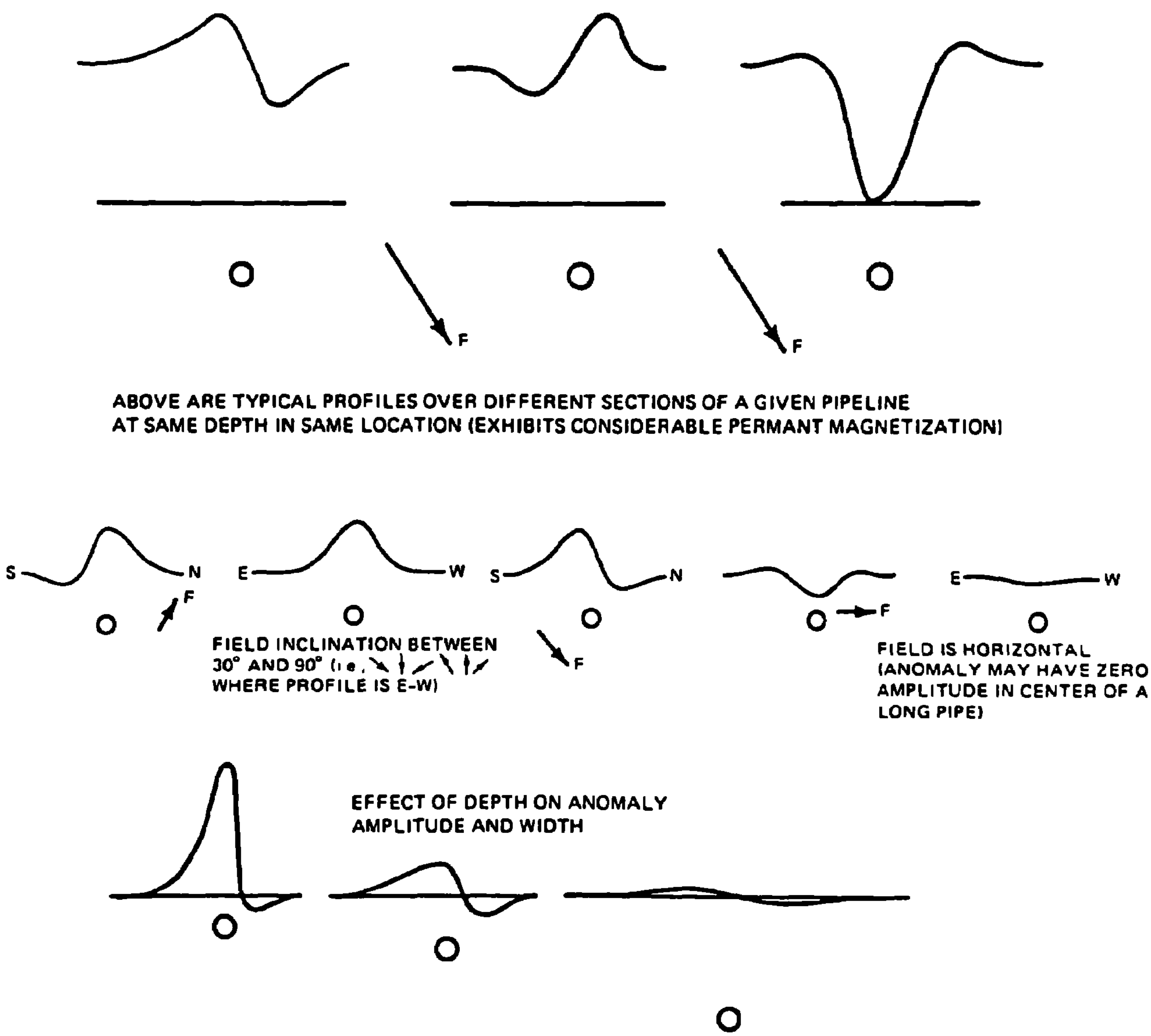


Figure 25. Different effects of pipeline on the shape of a curve plotted from readings obtained from a magnetometer (Breiner 1973).

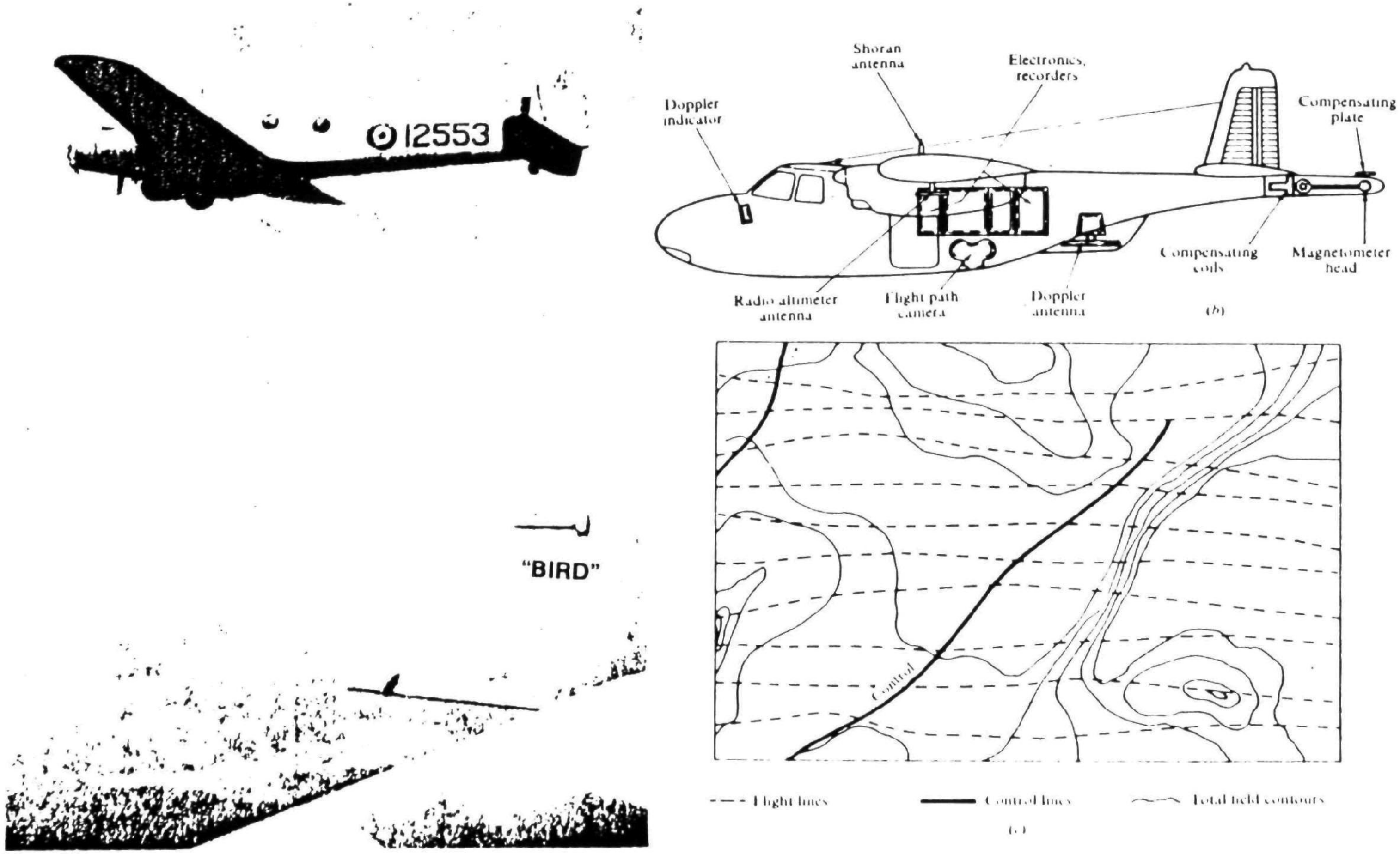


Figure 26. Airborne magnetometer mounted in an airplane or suspended from a "bird" and contour map produced from a hypothetical aerial survey (Telford et al. 1976).

Although aerial magnetometer surveys have not been specifically applied to searches for abandoned wells, anomalies attributed to casings have been identified during aerial magnetometer surveys for mineral exploration (Barret, 1931). The EPA is currently conducting a study to determine the effectiveness of aerial reconnaissance to determine the location of well casings. Although different conditions change the flight height and flight line spacing, preliminary analysis has indicated that an aircraft height of between 100 to 200 feet with a spacing of approximately 400 feet for flight lines may be necessary for definition of the casings (Frischknecht, et al., 1983). Aerial reconnaissance at these heights may be limited to rural areas of low density population because the Federal Aviation Administration (FAA) sets restrictions on the height above and lateral distance from occupied buildings that planes may fly. In special cases, variances may be obtained. Application may further be restricted to rural areas to help eliminate the spurious effects of cultural features on the magnetic survey and to simplify interpretation.

Subsurface magnetometers may be useful for finding buried casings or for determining their depth below the ground surface. Sensors lowered into a nearby uncased borehole may provide the direction, distance and depth of a casing that is located within 15 to 18 horizontal feet from the sensing point (Baltosser and Honea, 1976). The equipment is mounted on a truck and operated by a two-man crew in a manner similar to logging techniques used in the petroleum industry. Operation of the equipment and interpretation of the data requires specific expertise and cannot be performed by a lay person. Application of subsurface techniques to well casings whose locations are known assist in determining the methods necessary to plug or replug the abandoned well.

COST

The cost of conducting a ground-based magnetometer search for metal casing and metal objects associated with oil and gas drilling and production operations is dependent on the cost of the equipment, the time and manpower necessary to conduct the search and the time necessary to perform any needed interpretations. Magnetometers range in price from $625 for a hand-held fluxgate magnetometer to over $4,000 for high precision recording magnetometers. Truck-mounted equipment is available for a purchase price of around $7,500. Rental of some types of equipment may be possible. Typical monthly rental charges for proton magnetometers vary from $350 to $700.

Manpower requirements will vary with the familiarity of the individual with the equipment and local drilling and production practices. Manpower requirements will also depend on the grid spacing, the size of the area to be searched and the success in quickly locating the abandoned well. The expertise of the individual who performs the search must necessarily increase with the sophistication of the equipment employed. Hand-held continuously scanning magnetometers can be operated with a minimum of expertise, while more advanced magnetometers require a knowledge of the instrument and may require formal interpretation of data.

Professional magnetometer searches may also be available. Individuals familiar with the equipment and local drilling practices may provide a more rapid and complete survey of an area. Cost associated with professional services range from $20 per hour plus travel and expenses to over $150 per hour when travel and per diem is included.

Aerial magnetometer reconnaissance is always performed by a professional company and requires interpretation of the data before the presence of well casings can be determined. The cost of aerial magnetometer surveys depends on the area to be covered, the number and spacing of the flight lines and the time necessary for interpretation of the data. Because most other forms of aerial surveys are not conducted in as closely spaced grid patterns and at heights necessary for determining the location of abandoned wells, cost estimates are not readily available at this time. However, Frischknecht et al., (1983) have made limited cost estimates of $825 to $1,320 per square mile based on informal discussions with one contractor. In general, because of the initial cost of mobilizing the aircraft and equipment, the area being surveyed must be large enough to warrant the initial investment.

Only professional companies provide subsurface magnetometer surveys. The cost associated with a survey is dependent upon the mobilization cost for the equipment, the transportation cost for bringing the equipment to the site and the amount of time necessary to perform the log and analyze the results. A reasonable cost estimate for this service would be approximately $3000 per day. Additional costs may be incurred if a special uncased borehole needs to be drilled so that the log can be run.

ADVANTAGES AND DISADVANTAGES

Magnetometers can be used to perform surface, airborne or subsurface reconnaissance. Surface surveys may help to determine the location of metallic well casings and metal objects associated with drilling and production activities. A variety of magnetometers may be used. The most commonly available instruments are fluxgate and proton magnetometers. The fluxgate magnetometer is fairly inexpensive, can be operated by an individual with minimal training and provides a continuous output usually in the form of an audible signal. A proton magnetometer is more expensive, provides readings at selected locations, requires more expertise to operate and may require interpretation of data. Both instruments are portable and suitable for finding ferrous objects at shallow depths. The equipment can be used in all types of terrain and vegetative cover although readings may be affected by cultural features such as power lines, buildings, fences and other ferrous sources. Field methods may require a labor intensive effort.

Aerial surveys may provide an overview of an area to determine the presence of well casings. Aerial surveys are most suitable for use in rural areas with a low population density because of the interference of cultural features on the magnetometer readings and the FAA restrictions on the flight height of airplanes. The survey may be expensive in terms of cash outlay, but may be cost effective on a per well basis. Interpretation of the data obtained from an aerial survey must be performed by a professional. The evidence of magnetic anomalies must then be checked through the use of ground search methods to field locate abandoned well casings.

Subsurface surveys may be used to determine the location of abandoned well casings at depths below the surface of the ground. This method is expensive and is limited in application to wells within 15 to 18 feet of the well being logged.

Magnetometers are limited to finding objects and casing composed of ferrous metal. Therefore, this method can only be applied when metal casing is present or when ferrous metal objects associated with drilling activities still remain at the site. This method should be used in conjunction with other methods to actually field locate abandoned wells.

CASE HISTORIES

Searches for well casings using magnetometers may be performed for a variety of reasons. The case histories listed below provide examples of searches that were conducted using magnetometers and detail the reasons the searches were conducted.

Case #1

There is often a need to determine the location of abandoned wells for replugging or to reopen the hole for production. In Illinois, a search for one abandoned well began with obtaining the original plat and surveying the marked distances in the field. When this was accomplished, the searcher guessed by knowledge of drilling practices that the well would have most probably been located about 200 feet uphill of the recorded site. A detailed search of the area with a fluxgate magnetometer found the location of the casing within an hour (K. Alwredge, personal communication, 1982).

Case #2

The practice of constructing domestic water wells with casing that does not extend above the ground surface is fairly widespread. The necessity to locate these wells for repairs where no surface expression is evident is common. The well casings can be located by walking over the area using a hand held magnetometer. Casings as deep as 6 feet have been located using this method. The use of the magnetometer to locate the casing results in the saving of considerable excavation time and effort (B. Jacoby, personal communication, 1982).

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SECTION 10

COMBUSTIBLE GAS INDICATORS

SYNOSPIS

Combustible gas indicators can be used in intensive field searches to detect the presence of hydrocarbons emitted from either cased or uncased abandoned wells. Combustible gas indicators are inexpensive, portable pieces of equipment which require no specialized knowledge to operate or interpret the output. They are suitable for operation in all types of terrain and in low vegetative cover. This method should be used in conjunction with other search methods to narrow the area of review before employing the use of the detector. Because of wind dispersion and the necessity for hydrocarbons to be present in detectable amounts, the combustible gas indicator has a limited application for locating abandoned wells.

DISCUSSION AND PROCEDURES

Combustible gas indicators are designed to detect and measure combustible gases or vapors in the air. The indicators are commonly used to detect gases such as methane or natural gas. Traditional applications of combustible gas detection equipment include: 1) testing manholes or sewers, 2) locating leaks in pipelines, 3) testing confined areas in sewage disposal plants and 4) testing enclosed areas such as the insides of tanks or vessels.

Combustible gas indicators are available with a wide variety of sensors. Most instruments operate on the same principle. A sample of gas is drawn through an aspirator bulb and comes in contact with a heated platinum filament. The filament is heated to operating temperature by an electric current. When the gas contacts the heated filament, combustion of the gas raises the temperature of the filament in proportion to the amount of combustible gas present. A wheatstone bridge circuit measures the change in electrical resistance due to the temperature rise. The value is usually expressed as a digital readout or is indicated by a needle deflection on a meter scale. Audible alarms which may be preset to any desired hydrocarbon detection level are available on some models. Gas concentrations from 0 to 100% of the lower explosive limit (LEL) are typically measured by this type of equipment.

A combustible gas indicator is a lightweight portable instrument which can easily be operated by one individual without specific training

(Figure 27). The equipment is suitable for operation in all types of terrain and in most types of vegetative cover.

In many abandoned or improperly plugged wells, hydrocarbons or other gases may be conducted to the surface. Methane, which is the most abundant gas associated with oil and gas production, may be detected by a combustible gas indicator if there is sufficient quantity present. A combustible gas indicator may be useful in intensive field searches for abandoned wells. The method may be useful for either cased wells or wells which have had the casing removed provided that a direct outlet from the source of the hydrocarbons to the surface exists.

When conducting a survey, the ambient background concentration of hydrocarbons in the area must be established to allow for natural and industrial hydrocarbon emissions. Measured levels of hydrocarbons above the ambient background level may indicate the presence of an abandoned oil and gas well. Hydrocarbon emissions from an abandoned well are dependent upon the efficiency of the original plugging operation and the subsequent gas pressure buildup in the wellbore. Gases are quickly dispersed by wind. As a result, measurements must be made with the instrument close to the ground. Establishment of a closely spaced grid system may be helpful in finding the source of the emissions. According to Johnston et al., (1973), most of the detectable methane will occur directly over the wellbore itself or in a radius of one to two feet around the wellbore. Of the wells examined in a field study, no wells had detectable ground emissions at distances farther than two feet from the wellbore. Beyond this distance, the methane is too dispersed to be measured as a significant increase above the ambient background level (Figure 28).

COST

The cost of conducting a survey with combustible gas indicators is dependent on the cost of the equipment and the manpower necessary to conduct the search. It is possible to purchase inexpensive combustible gas indicators ranging in price from $225 to $400. More sensitive equipment or accessories to provide additional sensors and more convenient equipment operation or storage will increase the cost.

Manpower requirements necessary to conduct the search should be relatively small because the equipment is used only when the search area has been narrowed significantly by other searching methods. Additionally, operation of the equipment is quickly and easily performed by an individual with a minimal amount of training.

ADVANTAGES AND DISADVANTAGES

Combustible gas detectors can be used in an intensive field search to help locate the presence of cased or uncased abandoned wells. The equipment is portable, inexpensive and can be operated by an individual

Figure 27. Operation of combustible gas indicator (Mine Safety Appliances Co. product literature).

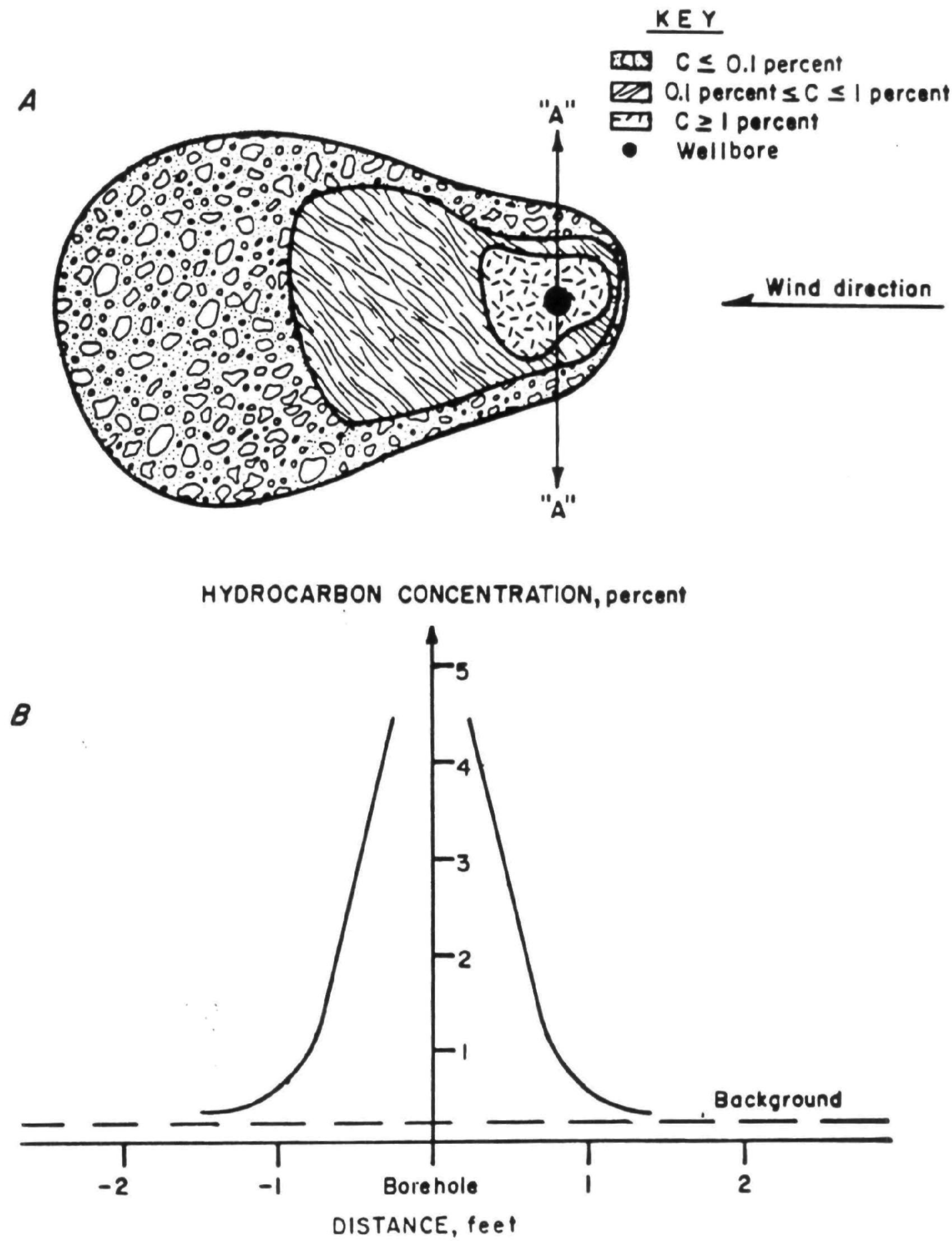

Figure 28. Graphic representation of decreases in methane concentration as search probe is moved from center of wellbore (Johnston et al. 1973).

with limited training on the instrument. The equipment is suitable for use in all types of terrain and low vegetative cover.

The method has limited application for sites where a direct connection with the hydrocarbon source to the surface exists. The combustible gas indicator should only be used when the search area has been narrowed to a smaller size by other searching methods. Even when the indicator is used to search a small area and passed directly over the well, insufficient amounts of hydrocarbons either due to low hydrocarbon production from the well or due to dispersal of hydrocarbons by the wind will render the detector useless. Other searching methods such as with metal detectors provide a low cost piece of equipment which is much more versatile. Therefore, combustible gas indicators are best applied in very site-specific applications.

REFERENCES

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SECTION 11

EXCAVATION

SYNOPSIS

Excavation is the final procedure used to verify the presence or absence of evidence of a casing, wellbore or objects associated with drilling and production activities. Excavation may be accomplished by shovel or by larger equipment such as a backhoe. The excavated area may be large or very small depending on the success in finding the desired object and the proximity of the initial site of excavation to the point where either the object was uncovered or excavation ceased. Excavation is most successful when used in combinatio- with the other methods described in this report. Although excavation may not produce the desired results, this method should always be employed in some form when the well is not visible and when exact location and verification of an abandoned well is necessary.

DISCUSSION AND PROCEDURES

Excavation is the process of digging up or uncovering well casings or objects associated with well-drilling activities. Excavation is usually the last step in locating an abandoned well which is not visible from the surface. A preliminary search using a combination of any of the methods previously described or as described in the second portion of this report should have been employed to yield a reasonable location of the well. Cased or uncased wells may be located in this manner. Soil discoloration in and around the well caused by drilling and production activities offers clues to the well location.

Procedures for earthmoving may vary depending on the area that needs to be excavated and the nature of the survey. If a well has been pinpointed by magnetic surveying or methane detection, a shovel may be used to excavate the area. For less industrious individuals, a backhoe may perform the excavating. Sometimes a larger area will be excavated to a depth of two to three feet. Clues in soil discoloration as well as buried objects are observed. Excavation is used to verify findings by other searching methods; widespread excavation may be used where other searching methods have proven unsuccessful.

COST

The cost of excavation depends on the area excavated and the tools and manpower necessary to complete the task. The excavation of shallow objects with a shovel is generally not considered as an additional cost in a general survey (shovels can be purchased for between $5.00 and $20.00). However, the use of larger equipment such as a backhoe or the intensive use of manpower to uncover deep or numerous objects may require a larger expenditure. Rental of a backhoe (complete with operator) usually ranges from $30 to $50 per hour.

ADVANTAGES AND DISADVANTAGES

Excavation may provide a verification of the location of a well casing, an uncased hole or objects associated with well drilling and production activities. This method should only be used in combination with other searching methods which have pinpointed a logical place for excavation. Excavation with large equipment can be accomplished quickly, but must be done carefully to avoid obliteration of the well. The time and manpower requirements of this method are extremely variable. Excavation is a necessary procedure to verify any buried well location, but may involve the moving of large quantities of soil without concrete results.

CASE HISTORY

The location of an abandoned well in Lea County, New Mexico was necessary to ensure the wellbore integrity for pending waterflood operations. The well had been drilled in 1933 and abandoned in accordance with the regulations in existence at the time. The location of the well was determined from the original survey description records and the well site was then resurveyed in the field. A backhoe was used to begin excavation in a grid pattern until evidence of the old cellar and pits were discovered. This led to the location of the remaining casing which had been cut off below ground level during the original abandonment (R. Phillips, personal communication, 1982).

SECTION 12

ELECTRICAL RESISTIVITY

SYNOPSIS

Electrical resistivity surveys may help to field locate cased abandoned wells and may be used to trace ground-water contamination plumes with high specific conductance to find an abandoned well which is the source of the contamination. Electrical resistivity surveys measure the apparent resistivity of the earth by injecting current into the ground and measuring the resultant potential field between two electrodes. While a metal casing will influence the results of an electrical resistivity survey, the anomaly may not be able to be distinguished from the overall results. Ground-water contamination surveys are more complex and require detailed interpretation of the data. An electrical resistivity survey is more time consuming to conduct than other methods because electrical probes must be placed into the ground and removed after each reading is taken. Electrical resistivity surveys are less cost-effective than other methods which will detect metal casing.

DISCUSSION AND PROCEDURES

Electrical resistivity surveys are designed to measure the apparent resistivity of subsurface materials. The method is based on the premise that differences in the electrical resistance of soils and rock will alter an electrical current passing through them (Tapp, 1960). Electrical resistivity surveys have traditionally been used for mineral and ground-water exploration and for studying the engineering properties of the materials of the earth (Horton et al., 1981). More recently, electrical resistivity has been applied to detecting and mapping ground-water contamination (Kelly, 1976; Cartwright and McComas, 1968; Stollar and Roux, 1975; Fink and Aulenbach, 1974; Warner, 1969).

The electrical resistivity technique induces a measured amount of very low frequency (<1 Hz) current to flow through the ground from a pair of electrodes some known distance apart (Zohdy et al., 1974) (Figure 29). Variations in the thickness, configuration, depth and saturation of the geologic materials alter the current path in the earth. A second pair of electrodes measures the resultant potential field between the two potential electrodes (Evans, 1982). Based on the values of current, voltage and electrode geometry, the apparent resistivity can be calculated (Tapp, 1960). The results are expressed as a graph showing apparent resistivity versus depth, as a contoured map of the site or as a curve which is used

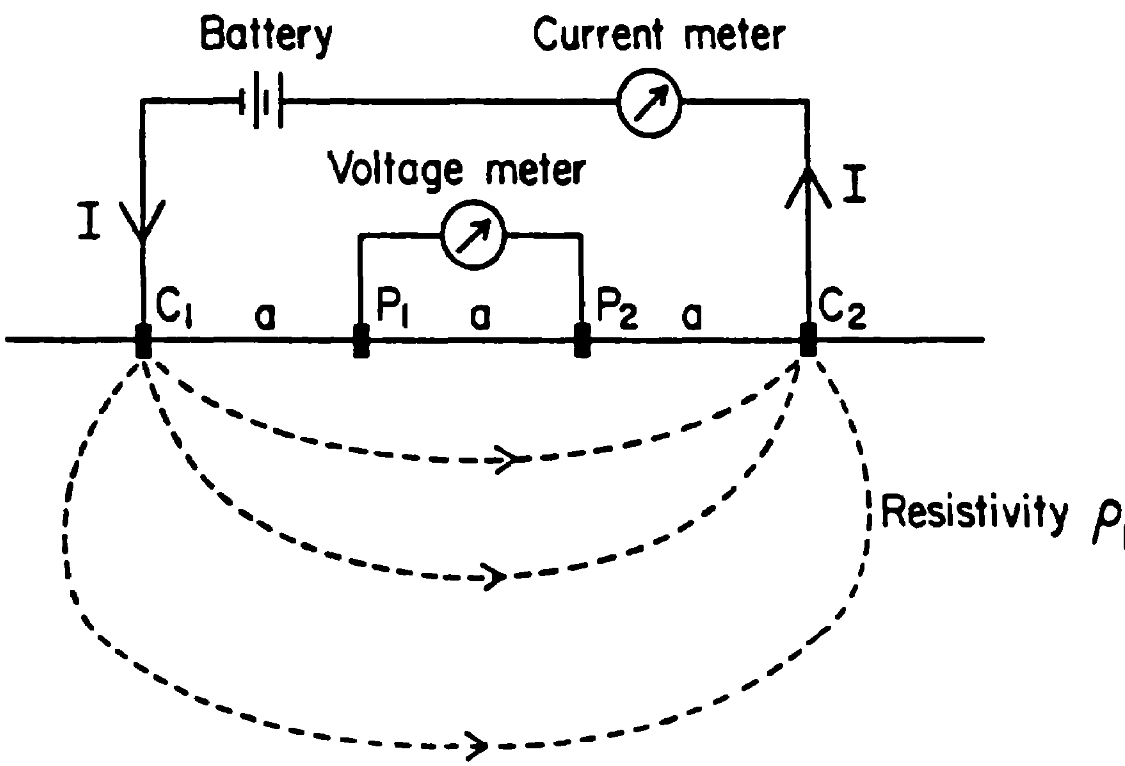

Figure 29. Diagram showing basic concept of electrical resistivity measurement (Mooney 1980).

to evaluate depth and thickness of subsurface layers with differing resistivities (Tapp, 1960; Schwartz and McClymot, 1977; Evans et al., 1982).

The basic electrical resistivity equipment consists of the resistivity measuring unit, four electrodes and four reels of wire (EPA, 1978) (Figure 30). The equipment used for shallow surveys is portable and can be carried from station to station. Electrical resistivity surveys are generally suitable for use in most types of terrain and vegetation. However certain factors may discourage the use of this method. Care should be exercised when conducting a survey in areas where the surface is wet because electrical shorts in the wires may occur if the wires are not properly insulated. Dry soils may also cause problems because proper electrical contact cannot be achieved. Vegetative cover such as dense brush or trees can also present difficulty either in placing the electrodes along a straight line or in attaching the wires and electrodes to the equipment. Additionally, the equipment cannot be used in urban areas where the electrodes cannot be inserted into the ground.

An electrical survey is conducted by inserting the electrical probes into the ground along a straight line (Figure 31). The spacing of the electrodes roughly determines the effective depth of the survey (Tapp, 1960). Therefore, the closer the electrodes are spaced, the shallower the depth of the survey. Spacings of 5, 10, 20, 50 and 100 feet are common for shallow electrical surveys, although the spacing of the probes varies dramatically from site to site and with differing applications.

Generally, two types of surveys, either profiling or sounding, are conducted. A horizontal profile of the area is obtained by keeping the electrode spacing constant and moving the electrodes to different stations on the site after each measurement is made (Zohdy et al., 1974). A vertical sounding involves progressively expanding the electrode spacing away from the center of the station until the desired maximum depth readings are obtained. The entire process is then repeated for each separate station (Schwartz and McClymont, 1976).

The results obtained from an electrical resistivity survey can be distorted by cultural features such as pipelines, oil and water tanks, metal fences, overhead power lines and transformers (Anonymous, 1971). Complex geology may also make the results difficult to interpret. To aid in interpretation, an electrical resistivity survey normally is conducted in areas where resistivity values can be correlated with geologic data such as lithologic logs (Schwartz and McClymont, 1977). Because of the intricacies involved in interpretation, considerable expertise is necessary to properly interpret the data. Today, interpretation is usually accomplished with the aid of a computer or programmable calculator.

Electrical resistivity has not been specifically applied to searches for abandoned wells. However, Holladay (1982) has indicated that steel oil well casings may produce an anomaly that is similar or greater in magnitude than other cultural sources such as fences, power lines and pipelines. An

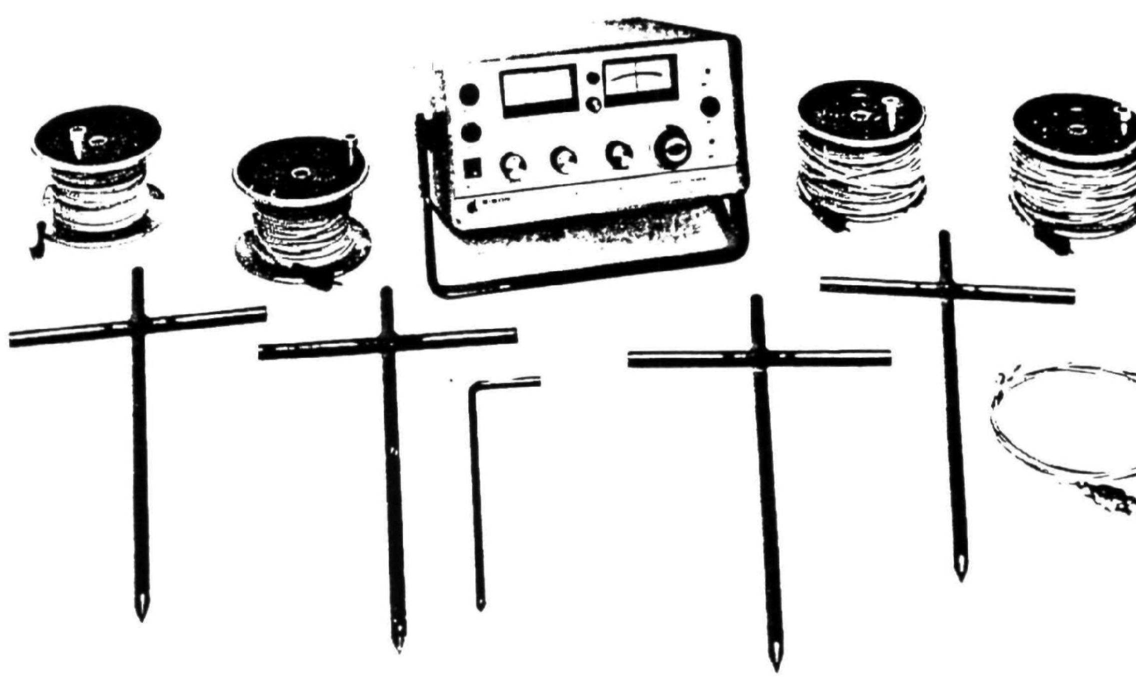

Figure 30. Electrical resistivity survey equipment (Bison Instruments Inc. instruction manual).

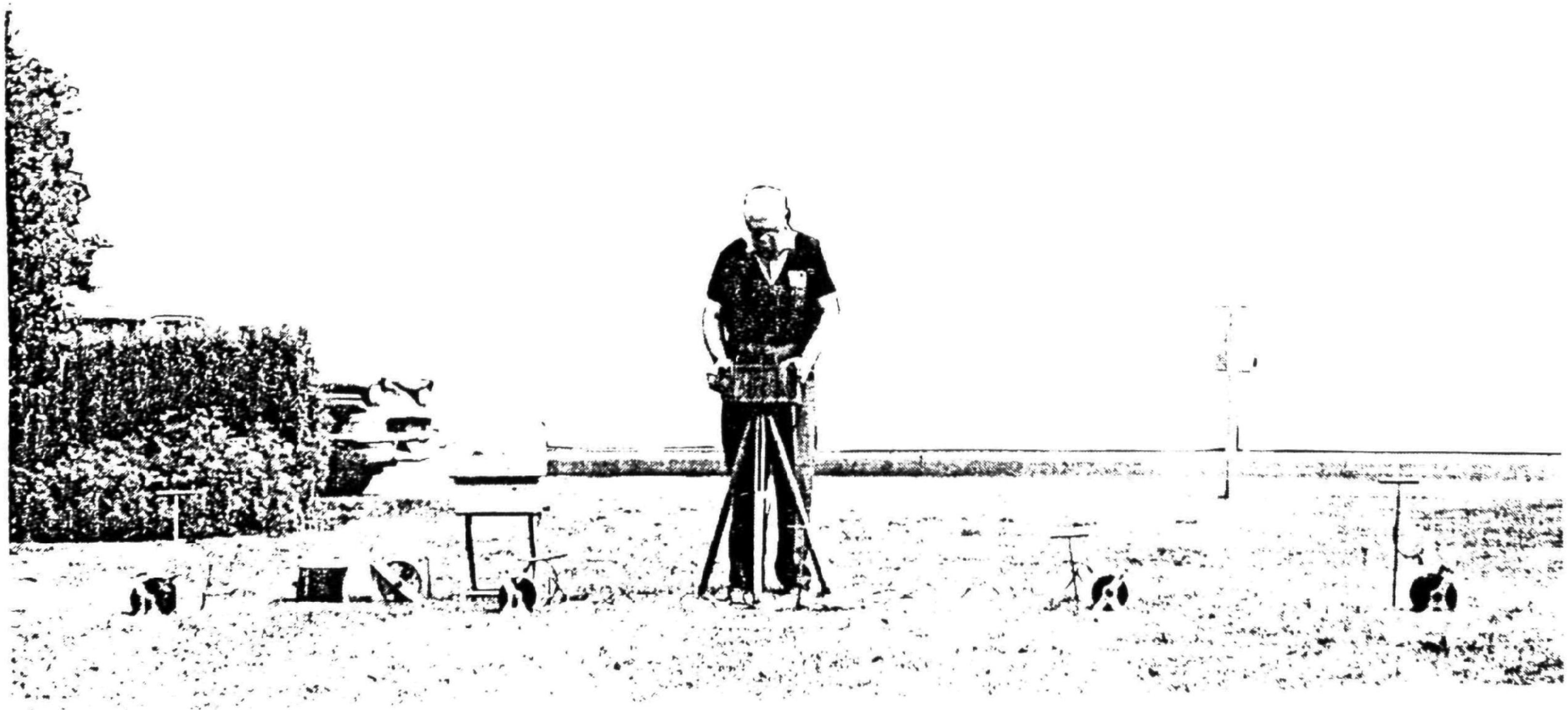

Figure 31. Field operation of electrical resistivity equipment (Anonymous 1971).

experienced geophysical surveyor may be able to recognize the anomaly in the field and determine the cultural feature which may be causing the disturbance (Anonymous, 1971). If this is possible, electrical resistivity surveys may be applicable to finding cased abandoned wells without the necessity for extensive interpretation of all the data obtained from the survey.

Electrical resistivity has recently been used to trace ground-water contamination plumes with a high specific conductance from such sources as landfills, sewage treatment effluent, salt piles, septic tanks and brine pits (Kelly, 1976; International Resource Consultants and Zonge Engineering, 1979). Therefore, electrical resistivity may be used as a tool to assist in identifying ground-water contamination caused by saltwater migrating through an abandoned well. Although electrical resistivity has not been extensively used for this purpose, it may prove moderately successful in defining the point source of brine leakage from the abandoned well. Other sources of high specific conductance present at the well such as brine spillage during or after drilling operations or brine associated with pits may interfere with the survey results and make it more difficult to pinpoint the location of the abandoned well. EPA (1978), has detailed the application and success of using electrical resistivity surveys to provide a good definition of the area of ground-water contamination at a number of hypothetical sites. Others have been successful in actually detecting and mapping ground-water contamination plumes (Kelly, 1976; Cartwright and McComas, 1968; Stollar and Roux, 1975; Fink and Aulenbach, 1974; Warner, 1969).

COST

The cost of an electrical resistivity survey varies depending on the cost of the equipment, station density, the size of the area evaluated, the type of survey, the manpower required and the extent of interpretation of the data. Equipment costs range from $2500 to $6600 with the average cost of survey equipment approximately $3500. Equipment may be available for rental at costs ranging from $560 per week to $700 per month.

An electrical resistivity survey is usually performed by two or three member crews. Under normal conditions, the crew may be able to take from 20 to 50 readings in a day with a single electrode spacing; 8 to 15 soundings with 7 readings at each station could also be completed in one day. Costs for professional field surveys range from $25 to $35 per hour per crew member plus expenses. In addition to obtaining the raw data, interpretation must be performed for ground-water contamination surveys. The time required for interpretation will vary greatly depending on the site. Costs associated with interpretation range from $60 to $80 per hour; for complicated sites it may take two to three days to perform the necessary interpretation.

ADVANTAGES AND DISADVANTAGES

Electrical resistivity surveys may be applicable for finding the location of cased abandoned wells. By using a fixed electrode spacing between 5 and 10 feet, anomalies created by casing at depths up to ten feet below the surface may be detectable without extensive interpretation.

Although 20 to 50 readings per day can be obtained using a fixed electrode spacing, resistivity surveys are time consuming when compared to other methods. The electrodes must be inserted into the ground and removed after every reading. Electrical surveys are not applicable at all sites and should not be conducted where terrain or vegetative cover prohibits the insertion of electrodes into the ground or the correct the alignment of the electrodes. The cost of the survey is relatively expensive when compared to other methods which are applicable for finding cased abandoned wells.

Electrical resistivity may also be applicable for determining the extent of a plume of contaminated ground water with high specific conductance. If contamination emanates from an abandoned well, an electrical resistivity survey may be used to delineate the shape of the plume and may help to locate the well. This application would be considerably more costly due to the extensive interpretation of the data that would be required. This application assumes contamination has already occurred and that the source can be traced to an abandoned well.

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SECTION 13

ELECTROMAGNETIC CONDUCTIVITY

SYNOPSIS

Electromagnetic conductivity may have application for determining the presence and field location of cased abandoned wells. The method may also be able to detect soil disturbances associated with drilling activities or plumes of contaminated ground water with high salinity. This, in turn, may help to better determine the location of an abandoned well. Electromagnetic conductivity surveys provide a geophysical technique which can be conducted relatively quickly. The equipment is portable and can be operated in most types of terrain and vegetative cover, however the operation of the equipment and the interpretation of the data require the services of a professional.

DISCUSSION AND PROCEDURES

Electromagnetic surveys measure variations in the conducitivity of the earth conductivity. These measurements are used to interpret subsurface features and identify buried objects. The measured electrical conductivity is influenced by the composition and porosity of the soil or rock, the conductivity of the fluids within the pore spaces and the composition of any man-made objects which are present (Evans et al., 1982). Electromagnetic conductivity has been used 1) in mineral exploration, 2) in archaeological exploration, 3) to map bedrock topography, 4) to locate pipes and 5) to detect the presence of waste containers, pipes and trenches at hazardous waste disposal sites (McNeill, 1980; Evans et al., 1982).

A variety of electromagnetic survey equipment is available for application to mineral exploration. However, only the relatively new electromagnetic techniques which provide a simple conductivity reading are discussed here.

An electromagnetic conductivity system consists of a power source, transmitter and receiver coils, and amplifier. An alternating current is passed through a transmitter coil which is placed near the surface (Telford et al., 1976). This current generates a magnetic field around the coil which induces electrical currents in the ground. The magnitude of the currents is a function of the subsurface conditions. The induced currents generate a secondary magnetic field (Figure 32). A receiver coil detects both the primary and secondary fields and the conductivity is calculated as

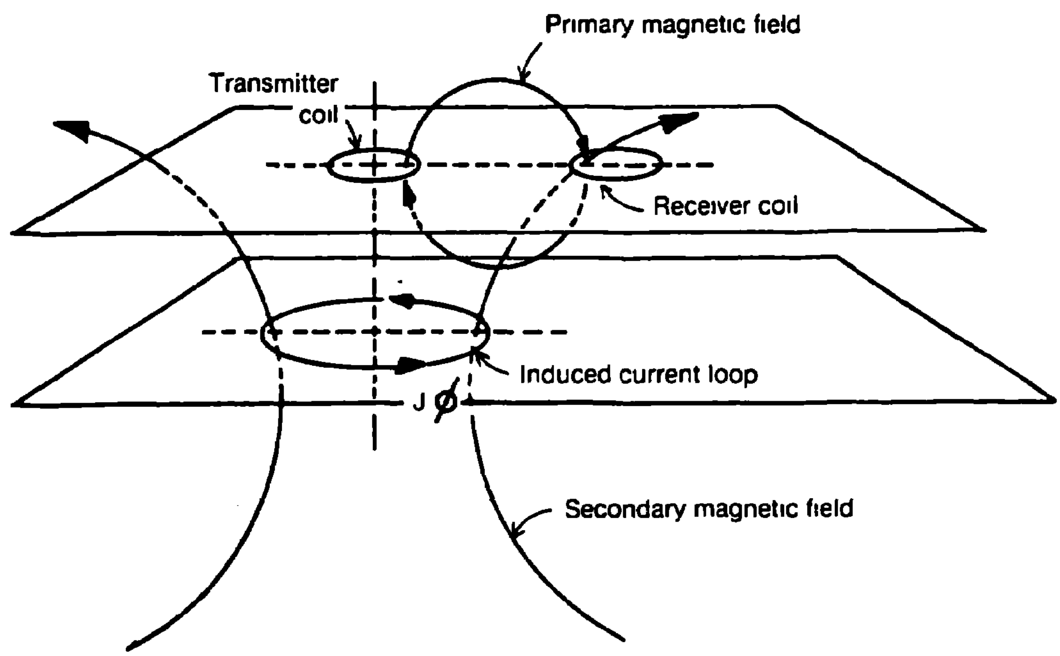

Figure 32. Diagram showing basic concept of electromagnetic conductivity measurement (McNeill 1982).

a function of the ratio between the primary and secondary fields (McNeill, 1982). This reading is usually displayed on a meter and may be recorded manually in writing or automatically on a strip chart or magnetic recorder.

Electromagnetic conductivity surveys require the establishment of a grid coordinate system to ensure systematic searching of the area. The spacing of the grid is determined by the intercoil spacing and the information desired from the survey. Grid spacings from 10 to 15 feet are common at hazardous waste disposal sites when delineation of trenches and buried drums is desired (Koerner et al., 1982). Spacings of 80 feet have been used to determine the extent of a contaminant plume with high salinity (McNeill, 1982).

The effective survey depth of electromagnetic conductivity equipment is related to the spacing between the two coils. Common coil spacings are 12, 33, 65 and 130 feet; effective survey depths range from 5 to 200 feet (Evans, 1982). In general, the nominal survey depth is 1 1/2 times the intercoil spacing. The effective depth may also be affected by nearby sources of "noise" such as power lines, fences or other surface or subsurface objects.

An electromagnetic conductivity survey is performed with relatively lightweight portable instruments which can be operated by one- or two-man crews depending on the equipment selected (Figure 33). Instrumentation is available which will provide either continuous readings or discrete readings at selected stations. The equipment can be operated to obtain a profile along a traverse by taking readings at a continuous depth or can be operated to obtain a depth profile at a single location by taking readings at various depths by changing the orientation of the coil. The speed of the survey depends on the number of readings taken, the grid spacing and the size of the area to be evaluated. The survey can be conducted in most types of terrain and in vegetative cover which is not heavily overgrown or wooded.

The data obtained from a survey may be voluminous and require interpretation by a trained professional. Computers are often employed to assist in data manipulation. The results are usually portrayed either as a profile of the traverse or as a contour map of the area.

No references were found to indicate that electromagnetic conductivity has been specifically applied to searches for abandoned wells. However, since electromagnetic conductivity has proven effective in locating buried drums at hazardous waste disposal sites, the method may also be applicable to finding buried metal casings. Electromagnetic conductivity surveys will not be useful in locating small metal objects associated with drilling and production activities because of the insensivity of the method to small objects. Despite the change in electromagnetic conductivity produced by metallic objects, Frishknecht et al., (1983) report that preliminary tests using portable electromagnetic equipment were only able to distinguish horizontal and not vertical pipe when test measurements were made at two well sites.

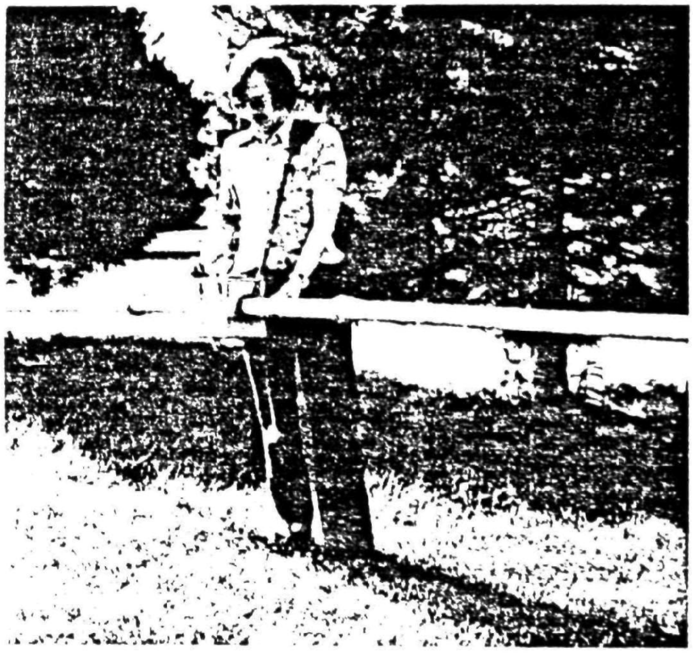

Figure 33. Field operation of electromagnetic conductivity equipment by one and two man crews (McNeill 1980).

Electromagnetic conductivity may also be applicable to finding evidence of larger surface disturbances associated with drilling activities. Brine pits which have been filled in may produce a large enough anomaly to be separated from the surrounding area. The procedure for locating such a disturbance would be similar to that for delineating a trench at a hazardous waste disposal site. Brine pits or other areas with high salinity will have a higher conductivity which may also be detectable. Additionally, it may be possible to map highly saline plumes of ground water using electromagnetic conductivity. The plume may then be traced back to its source which could be an abandoned well.

COST

The cost of an electromagnetic survey will be largely dependent on the area to be searched, the grid spacing necessary to achieve the desired results and the interpretation of the data. The cost of either purchasing or renting the equipment or having the search performed by a professional company must also be included. Portable electromagnetic survey equipment ranges in cost from $7,800 to $13,000. The equipment may be rented for costs ranging from $300 to $500 per week depending on the sensitivity of the desired equipment. If the equipment is either purchased or rented, a qualified professional will be needed to oversee the survey and interpret the data. It may be desirable, therefore, to employ the services of a professional company experienced in the operation of the equipment and the interpretation techniques. Costs typically range from $750 to $1000 per day plus travel expenses for a two-man crew. Additional costs may be incurred in verifying the location of a metal casing by excavation or by using other methods to locate the well when the general area of the well is delineated by the electromagnetic conductivity survey.

ADVANTAGES AND DISADVANTAGES

Electromagnetic conductivity surveys may have application for delineating the location of an abandoned well by indicating the presence of metal casing, soil disturbances associated with drilling and production activities or highly saline ground-water plumes. The method provides a relatively quick geophysical survey of the area at depths which can be as shallow as 5 feet or as deep as 200 feet. The equipment is portable and can be operated by either one or two people in all types of vegetation and terrain although readings may be affected by cultural features such as power lines.

The cost of an electromagnetic conductivity survey is relatively expensive when compared to other methods which are applicable for finding cased abandoned wells. Additionally, the survey must be performed by a professional who can correctly perform and interpret the results.

If the well does not contain metallic casing, the method may only be used to infer the location of the abandoned well. In this case, other methods may be required to specifically locate the well.

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SECTION 14

GROUND PENETRATING RADAR

SYNOPSIS

Ground penetrating radar may be a viable technique for determining the presence and field location of abandoned wells. Ground penetrating radar detects soil disturbances and buried metal objects, and therefore may be used to find both cased and uncased wells, metal objects and other soil disturbances caused by drilling and production activities. Geophysical surveys using radar are relatively expensive to perform and must be conducted and interpreted by trained professionals. Ground penetrating radar provides a continuous survey of the area. Output from the instrument is usually in the form of a graphic "image" which permits on-site field interpretation of the data.

DISCUSSION AND PROCEDURES

Ground penetrating radar uses high frequency radio waves to detect the presence and depth of natural subsurface features and man-made objects. The responses detected by the equipment are influenced by both natural phenomena such as bedding planes, clay content, moisture, voids and fractures, as well as by man-made objects and soil disturbances (Evans et al., 1982). Ground penetrating radar is a relatively new geophysical technique which has been used 1) to investigate archaeological sites, 2) to detect the presence of waste containers, pipes and trenches in hazardous waste investigations, 3) to locate sewer lines and buried cables, and 4) to profile lake and river bottoms (White and Brandwein, 1982; Yaffe et al., 1980).

A ground penetrating radar system consists of a transmitter, an antenna, a receiver and a graphic recorder. The equipment is normally mounted on a truck or in a van and the antenna is towed behind the vehicle. Pulses of electromagnetic frequencies ranging from 100 to 900 MHz are radiated into the ground from the antenna which is within a few inches of the surface (Koerner et al., 1982). The pulses of radar are reflected from subsurface interfaces which have different electrical properties (Evans et al., 1982). The reflected signals are received by the antenna, processed electronically and displayed on a recorder as a visual image or continuous cross section of the area along the traverse (Evans, 1982) (Figure 34). The time required for the pulse to travel down and back provides an indication of the depth of either the horizon or subsurface object (Koerner et al., 1982).

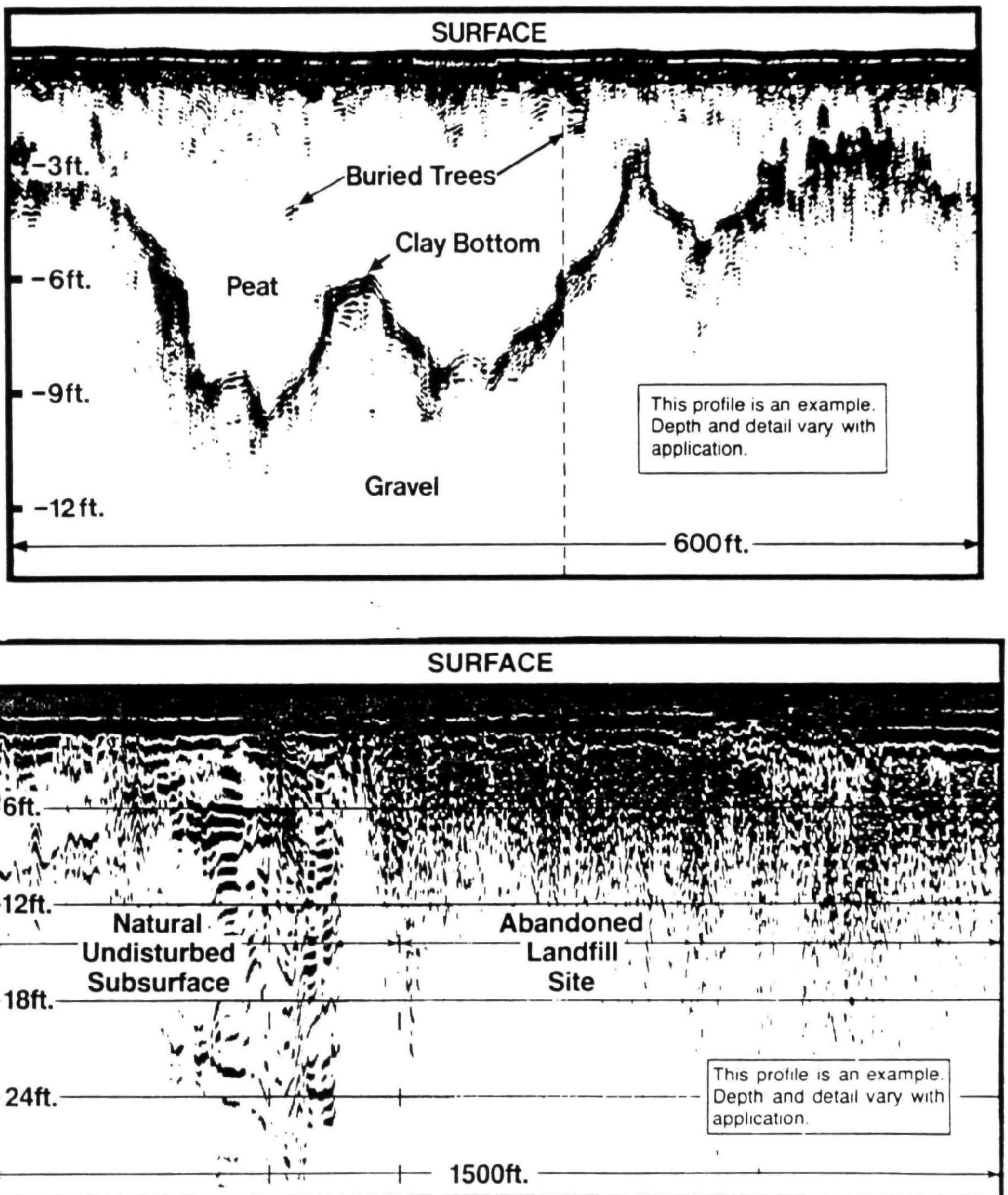

Figure 34. Example profiles obtained from a ground penetrating radar survey (Geophysical Survey Systems Inc.).

A ground penetrating radar survey requires the establishment of an appropriate grid coordinate system and the marking of the reference points on the ground. The spacing of the grid is determined by the desired coverage of the subsurface. The finer the grid pattern, the greater the resolution and coverage. Grid spacings of 10 feet have been used at hazardous waste disposal sites to survey the area for buried drums (Yaffe et al., 1980).

Depth of penetration of ground penetrating radar is limited by a variety of factors including clay content and the conductivity of the water within the pore spaces (White and Brandwein, 1982). The depth of penetration of the radar is very site specific, however, depths of 9 to 30 feet are commonly attained (Evans, 1982). By selecting the frequency emitted by the transmitter, the depth of penetration can be controlled to some degree. In general, the higher the frequency, the greater the resolution at shallow depths because the depth varies with the inverse square of the frequency (Yaffe et al., 1980). Because of the level of sophistication of the equipment, operation must be performed by a trained professional.

A survey is conducted by towing the antenna over the ground along an established traverse. The speed of the survey will depend on the coverage desired, but better resolution can be obtained by slowing the speed of the survey. The terrain must be level enough to accommodate the operation of the vehicle. According to Horton et al., (1981), brush is usually cleared and weeds and grass mowed to improve ease of operation at the site.

Data output usually consists of a seri.s of black and white images which form a graphic image of the subsurface with depth. The dark bands occur at positive and negative peaks and the light bands occur at the zero crossings between peaks (Horton et al., 1981). The output provides a preliminary analysis of the site in the field; however, interpretation is not always straightforward and requires the expertise of a professional.

Ground penetrating radar has not been specifically applied to searches for abandoned wells. However, wells have been identified when searches were conducted for other reasons (Figure 35). According to McKown and Sandness (1981), the use of ground penetrating radar does have potential application for the location of old wells and abandoned drill holes.

Since radar has proven effective in locating disturbed areas of earth in such applications as hazardous waste disposal sites (Yaffe et al., 1980), it should be possible to detect areas disturbed by drilling and production activities even if surface evidence is not present. Uncased wells, wells where the casing has been cut off at depth below the ground surface or pits used in drilling activities should provide a disturbance in soil compaction which results in a change in the electrical properties of the soil. This, in turn, may be detected by the radar. The ability of radar to determine the presence of metal may also make it valuable in determining the presence of wells which contain casing or in locating metal objects associated with drilling and production activities.

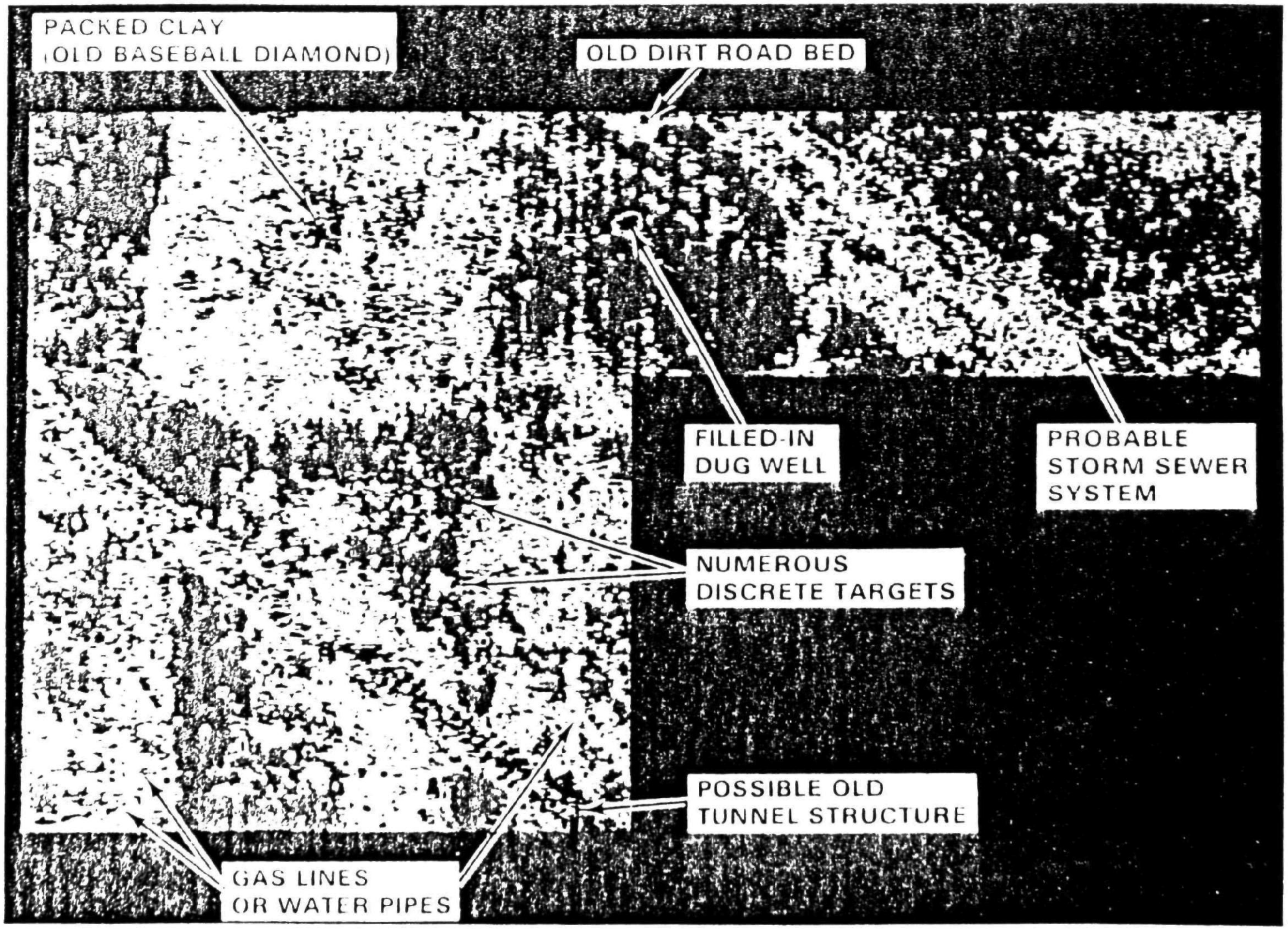

Figure 35. Computer produced map view of radar reflections at survey site (McKown and Sandness 1981).

COST

The cost of conducting a survey with ground penetrating radar is dependent on the desired resolution of the survey and the area to be searched. Due to the cost of the equipment ($25,000 to $45,000), equipment would not normally be purchased for this specific application. Costs for surveys may be site specific and related to the cost of equipment mobilization, but range from $1000 to $2000 per day. Costs generally include a raw data output such as produced from the graphic recorder. Additional graphic representations or interpretation are normally available at prices averaging from $40 to $60 per hour for labor with computer time and materials added as additional charges.

ADVANTAGES AND DISADVANTAGES

Ground penetrating radar may be applicable to delineating soil disturbances caused by the location of uncased or cased wells or other excavations associated with well drilling and production practices. The technique may also be applicable for locating metal casings and metal objects associated with drilling procedures. Surveys may be conducted fairly rapidly by truck mounted equipment. On site interpretation of the data is made possible by the graphics produced by the recorder. The display provides a continuous scan of the search area. Ground penetrating radar may be suitable for application to either cased or uncased wells at depths up to 25 feet and may provide an actual field location for the abandoned well.

Ground penetrating radar surveys are relatively expensive and must be conducted and interpreted by trained professionals. The equipment is normally vehicle-mounted and therefore requires access to the site. However, the equipment may also be hand-towed, thereby, requiring a smaller access area. Vegetation must be low and brush cleared from the site for efficient operation. Depth of penetration is extremely variable and may vary widely depending on the site conditions.

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SECTION 15

REMOTE SENSING

SYNOPSIS

Remote sensing is used to gather data about the surface of the earth using aircraft or satellite mounted sensors. Infrared imagery, which is comprised of color infrared or thermal infrared, detects selected wavelengths of electromagnetic radiation from the earth to produce an image. Color infrared is termed "false color" imagery because the image depicts natural objects in colors not seen in the visible light spectrum. Thermal infrared responds to temperature variations in the earth. Color infrared imagery may be applicable to delineating areas of vegetation stress associated with drilling operations. This, in turn, may be traced to find an abandoned well location. Thermal imagery may compliment a full remote sensing scan, but may have less direct application to finding abandoned wells than other imagery. A special survey must be conducted to obtain infrared imagery because it is not readily available from other sources. These methods are expensive because of the mobilization cost associated with the survey and also the need for professional interpretation of the data. However, the cost per square mile may be low in comparison to other methods.

DISCUSSION AND PROCEDURES

Remote sensing is used to gather information about the surface of the earth by using a sensor that is located above the surface. Remote sensing is usually accomplished by a sensing device that is mounted on an aircraft or in a satellite. Black and white aerial photographs, color photographs, color infrared and thermal infrared are all common types of remote sensing outputs. Black and white aerial photography is discussed in Section 7. Color photographs are interpreted very similarly. Infrared imagery will be discussed in this section.

Infrared imagery uses selected wavelengths of electromagnetic energy to produce an image. Wavelengths between 0.7 and 0.9 microns are recorded on infrared film to produce color infrared imagery. Wavelengths from 3 to 5 and 8 to 14 microns can be detected by a mechanical scanner to produce a thermal image (Sabins, 1978).

Color infrared imagery was originally developed by the military for determining the location of camouflaged targets (Avery, 1968). Civilian applications of the technology include detection of vegetation stress, identification of vegetation types and determination of geology by vegetation patterns (Sabins, 1978; Avery, 1968).

Color infrared imagery or "false color imagery" responds to the differences in the amount of radiation reflected by the objects being photographed. Color infrared film is similar to regular color film except that it is sensitive to green, red and infrared radiation (Avery, 1968). A yellow filter is used to remove the remaining blue light and therefore increase the contrast and resolution on the infrared film (Sabins, 1978). When processed, the image has colors which are "false" for most natural features. For example, healthy deciduous foliage appears bright red and clear water appears dark blue or black (Sabins, 1978).

If the vegetation is stressed or diseased, however, the infrared reflectivity of the leaves decreases and a "color change" can be seen even though the difference would not be visible to the naked eye. Color signatures will also change with the season as the reflectivity of a plant changes (Avery, 1968).

Thermal infrared imagery measures the amount of infrared energy (heat radiation) that is emitted from the surface being imaged. Thermal infrared imagery has been used to detect temperature-related phenomena such as coal refuse pile fires, forest fires, thermal pollution and volcanic activity (Deutsch, 1974; Thackrey, 1968). In addition, structural geologic mapping, ecological studies and archeological studies have been conducted using this technique (Bastuscheck, 1970).

Electromagnetic energy is emitted by any substance which has a temperature above absolute zero and, therefore, all solid objects (trees, rocks, animals, etc.) are sources of infrared radiation (Avery, 1968). The intensity of the radiation is related to the surface temperature of the emitting material (Wolfe, 1974). Since thermal radiation is absorbed by the glass lenses of a normal camera and cannot be recorded on film, an aircraft-mounted line-scanning imaging device is used to record radiation from 8 to 14 microns (Wolfe, 1971). A rotating mirror within the scanning device reflects the images onto an element sensitive to infrared radiation (Figure 36). The detector emits an electrical signal proportional to the intensity of the radiation (Sabins, 1978). The image created by the element is normally stored on magnetic tape and later transferred onto film (Sabins, 1973).

Thermal imagery displays the apparent temperature differences occurring in the surface being imaged. The resulting thermal imagery is a black and white image where warm or hot surfaces appear as light areas, while colder surfaces appear as darker areas (Figure 37). Typical thermal scanners may be sensitive to variations as small as 0.1°C (Sabins, 1978).

Neither color infrared nor thermal imagery are readily available for most areas. Therefore, a special aerial survey is normally required to obtain the imagery. Special care should be exercised to select the optimum

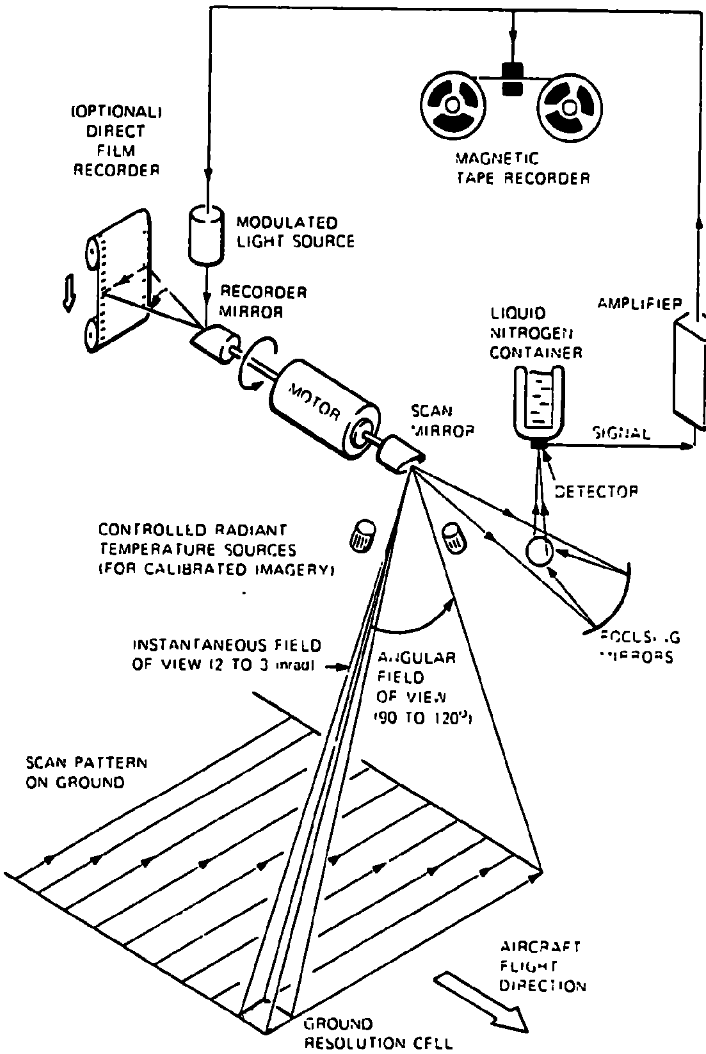

Figure 36. Diagram of thermal infrared scanner system (Sabins 1969).

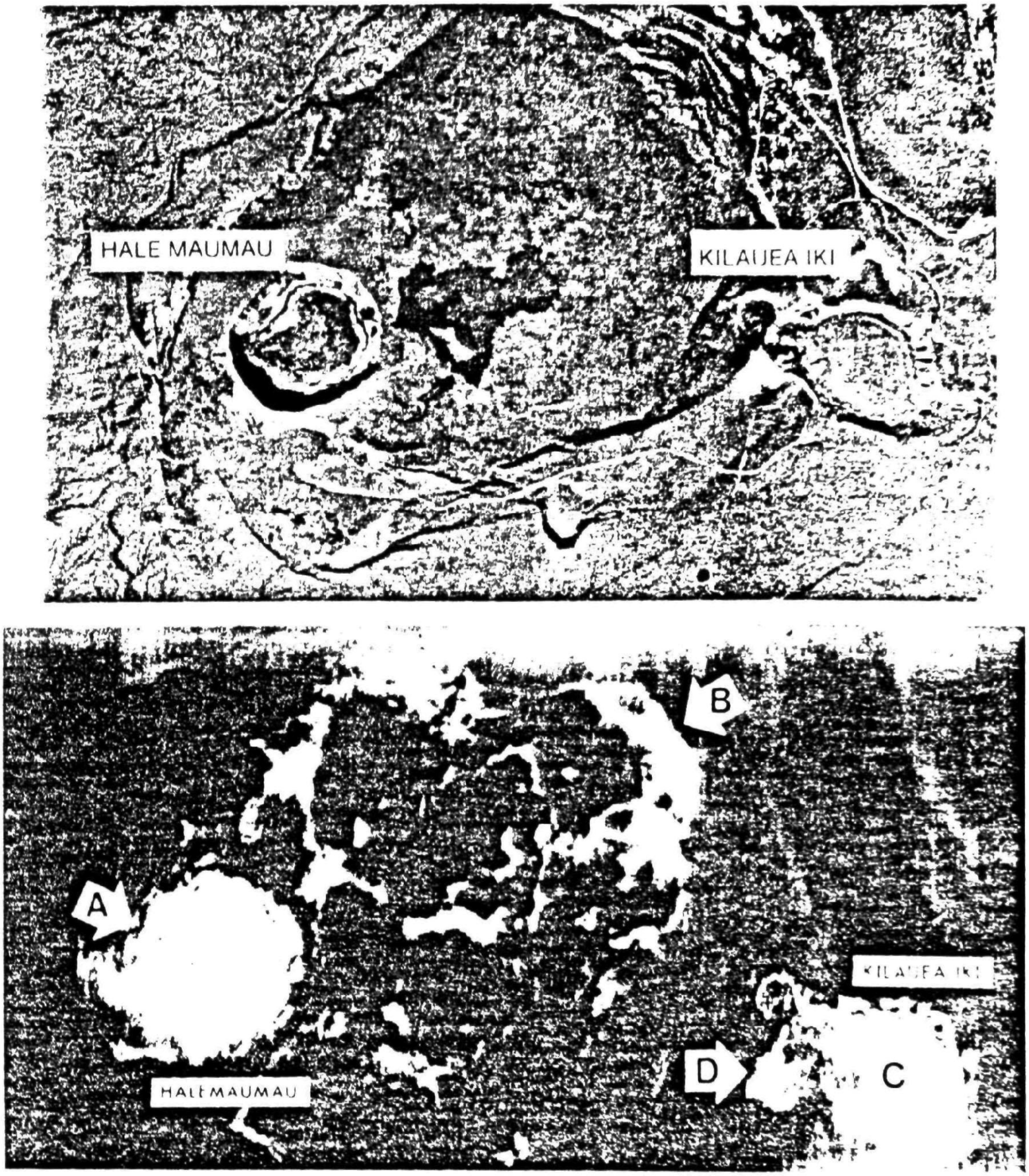

Figure 37. Thermal infrared image and panchromatic photograph showing Kilauea volcano, Hawaii (Fischer et al. 1964)

time of day and year when the imagery should be recorded. Both types of imagery require a minimum of cloud cover and can be photographed at any altitude. Color infrared is suitable only for daytime exposure, while day or night exposure is possible with thermal imagery (Sabins, 1978). If color infrared is to be used for vegetation stress, photographs should be taken when vegetation is evident. Thermal photography is affected by the diurnal effects of solar heating and cooling. Therefore, some objects which heat or cool rapidly may appear drastically different depending on the time of the day or night.

Because infrared imagery is displayed in the form of a picture, the assumption that the image may be easy to interpret is often made. However, the image created on either type of imagery is related to the amount of electromagnetic radiation reflected or emitted and not to the amount of visible light as in a normal photograph (Avery, 1968). Many factors such as the seasonal variations, different heat capacities of materials and moisture content must be understood before a correct interpretation of the true image can be made (Crouch, 1979; Avery, 1968). The trained eye of a professional is therefore required for accurate interpretation.

Neither color infrared nor thermal imagery has been specifically applied for locating abandoned wells. Color infrared may be applicable for delineating areas of stressed vegetation due to a high salt content of the soil. According to Myers (1970), salinity causes a reduction in the water uptake of plants which causes moisture stress. Additionally the growth of plants in saline soils is normally retarded. If the salinity was caused by brine associated with drilling and production activities, it may then be possible to study vegetation stress and trace it to an abandoned well site. No studies were found which would determine the persistence of salt through time in the soil and its associated effect on vegetation. It must be remembered that other factors such as disease also produce vegetation stress and ground verification would be necessary.

Thermal imagery may have less direct application for locating abandoned wells. It was originally hoped that due to the temperature differences associated with the bottom of a well and the surface of the ground that variations in the temperature might be distinguishable at the surface. Even with imagery collected at heights of 1000 to 2000 feet above the ground and flight line spacings of 800 to 1000 feet, the temperature differential would probably not be distinguishable as a point source (Ory, personal communication, 1983). However, thermal imagery may provide an additional remote sensing tool which can be used to verify or discern between variations on other types of imagery or photographs.

COST

Since neither color nor thermal infrared photography are readily available, the single largest cost is related to obtaining the imagery. This necessitates the hiring of a professional company to perform the survey. The single largest cost is associated with mobilization of the aircraft. For this reason, many companies are equipped to produce more than one type of imagery during a flight, thereby reducing the cost of each individual type of imagery. Typical charges associated with thermal scanning are usually not less than $20,000. Additional charges of between $1500 and $2000 a day plus charges to process and interpret the data are common. Color infrared photography is somewhat less expensive because the resolution is better and the photography can be taken from a higher altitude thereby reducing the number of flight lines necessary to cover a similar area.

ADVANTAGES AND DISADVANTAGES

Color infrared imagery may be applicable to finding areas of stressed vegetation associated with brine produced during drilling and production activities. This, in turn, may help to identify the location of an abandoned well. Thermal imagery, however, appears to have less direct application for delineating a point source of thermal variation associated with an abandoned well. Neither type of sensing is readily available and both require a special reconnaissance flight to obtain the desired imagery. This results in the method being relatively expensive. Thermal imagery is the more expensive of the two types of infrared imagery because it requires flights at lower altitudes and with more closely spaced flight lines than the color infrared. Both types of imagery require professional interpretation to ensure the best results. Once the photography has been interpreted, field verification of the location of the well must still be performed.

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SECTION 16

WATER LEVEL MEASUREMENT IN SURROUNDING WELLS

SYNOPSIS

Water levels in aquifers may be used to help locate either cased or uncased abandoned wells. This may be possible when pressures within a deep formation exceed the pressures within the aquifer and a pathway exists for migration of fluids to occur. Since water levels within an aquifer are affected by localized sources of recharge, the abandoned well may serve as a point of recharge and raise water levels in the vicinity of the well. Water-level measurements taken in surrounding wells may reflect the localized rise in water levels and the location of the abandoned well may be estimated.

Since water-level measurements can be made relatively quickly with no specialized equipment, data can be collected easily when existing wells are present. The water-level measurements must be interpreted within the local and regional hydrogeologic framework to accurately assess the situation. The absence of wells in the vicinity of the abandoned well precludes the use of this technique.

DISCUSSION AND PROCEDURES

Water levels in wells are the expression of the water table or of the hydrostatic pressure within an aquifer (Todd, 1980; Freeze and Cherry, 1979; Fetter, 1980; Walton, 1970). Each water level reflects the overall aquifer characteristics as well as local variations within the hydrogeologic framework. Water levels respond to many natural and artificial stimuli including pumping, injection, and precipitation. The reaction of the water level to those stimuli is a function of the type and duration of the event and the type of aquifer.

Aquifers are termed either confined or unconfined based on their geologic setting (Figure 38). A confined aquifer is overlain by a relatively impermeable layer called a confining bed (Davis and DeWeist, 1966). The layer restricts the water from moving upward. When a well is drilled into a confined aquifer, the pressure is released and the water rises to a level in the casing known as the piezometric surface. The source of replenishment of the aquifer is normally some distance away from the well, so local precipitation rarely affects water levels in a confined aquifer.

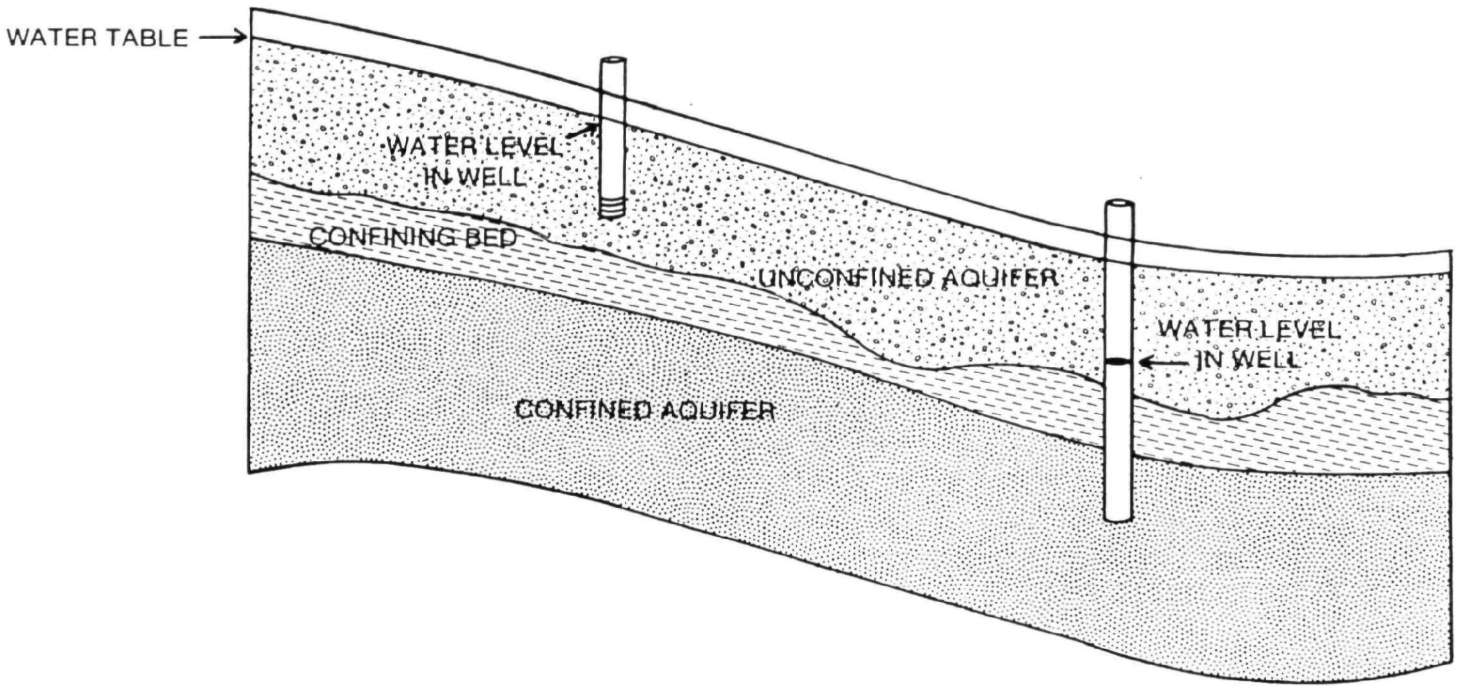

Figure 38. Diagram showing confined and unconfined aquifers.

An unconfined aquifer is not under pressure like a confined aquifer, but instead is under atmospheric pressure only (Walton, 1976). Water levels in an unconfined aquifer or in a well which penetrates an unconfined aquifer are a direct expression of the level of saturation of earth materials. The surface created by this upper limit of saturated geologic materials is called the water table. Local precipitation provides the recharge to an unconfined aquifer and thus affects water levels.

The type of aquifer also controls to a certain degree the effect which pumping a well will have on water levels. When wells are pumped, water levels decline in close proximity to the well. With time, the resultant cone of depression of the water table will spread out until the amount of water entering the cone is equal to the amount of water being removed from the well (Johnson, 1975). The effects on water levels of pumping wells can be predicted mathematically (Freeze and Cherry, 1979).

Water levels in wells are also influenced by their proximity to recharge points such as hills or discharge points such as valleys or streams. Water levels in unconfined aquifers tend to roughly parallel the topography of the area while water levels in confined aquifers tend to be more uniform over a larger area (Davis and DeWiest, 1966).

Because water levels in wells can be affected by localized sources of recharge or discharge, the location of an abandoned well may be determined by studying water levels in wells in the adjacent area. An abandoned well which is improperly sealed serves as a conduit which connects all the geologic formations that it penetrates. Water will move from formations with higher pressure into formations with lower pressure. If formation pressures are greater in the deeper formations associated with oil and gas, and if a pathway exists, the fluids will migrate upward into aquifers which have a lower pressure (Todd, 1980). This pressure differential may be natural or may arise when injection operations add pressure to the reservoir. If the injection zone is filled with fluid, the pressure is transmitted virtually instantaneously throughout the formation. If the formation is not full, the reservoir will begin to gradually fill as injection continues. The pressure may gradually build until it is sufficient to overcome the pressure in the overlying formations.

This point source of recharge through the abandoned well may be distinguished by anomalous increases in water levels which decrease approximately radially away from the source (Figure 39). The distance from the source at which an anomaly can be distinguished depends on the pressure differences between the formations, the effect of other localized recharge or discharge, the confined or unconfined nature of the aquifer and the characteristics which influence flow within the aquifer.

Water-level readings should be obtained from a number of existing wells that are distributed around the suspected location of the abandoned well. An attempt should be made where possible to obtain water-level readings which reflect the static water level with no influences from sources of recharge or discharge other than the abandoned well. This may

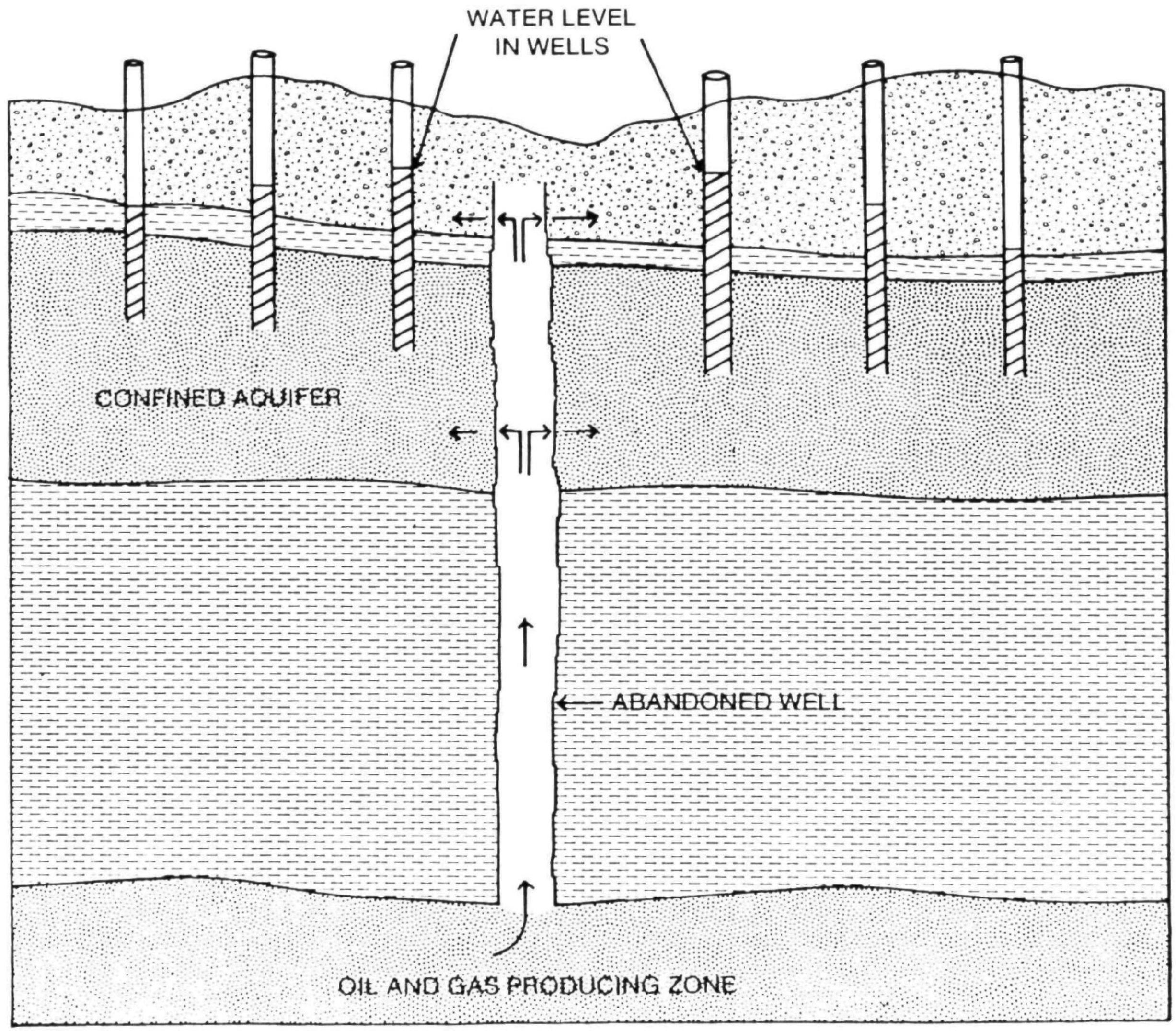

Figure 39. Diagram illustrating water level increases in wells surrounding an abandoned well.

be difficult, particularly where the water level in the well reflects the composite head from more than one aquifer. In order to adequately assess the water-level readings obtained from an area, it is necessary to have a complete understanding of the local and regional hydrogeology. The water-level readings must be reviewed within this framework to understand if a localized anomaly due to an abandoned well exists. Realizing that optimum conditions rarely exist, it may not be possible to gather enough information from existing wells either to determine if an anomaly exists or to locate the abandoned well with any degree of certainty. At this point, it would be necessary to determine if additional wells should be drilled or if other methods would be better suited to locating the abandoned well.

COST

The cost of determining the location of an abandoned well by observing water levels in the adjacent area depends on the number of wells to be sampled, the manpower necessary to obtain the water level measurements, the time necessary to assemble an understanding of the local hydrogeologic setting and the time to interpret the measured water levels within that framework. No specialized equipment and only a minimal amount of training of personnel is necessary to obtain water-level measurements and the measurements may be taken relatively quickly. Most of the time spent in measuring water levels will be related to travel time between the sites. The hydrogeology of an area may already be documented in published reports which are available for a small cost. If this is true, the time spent in defining the hydrogeologic framework can be reduced.

ADVANTAGES AND DISADVANTAGES

Water-level measurements in wells may be used to help locate either cased or uncased abandoned wells when pressures in the injection zone are higher than pressures in the aquifer and leakage between the formations is occurring. No specialized equipment is necessary to obtain water-level measurements and the measurements can be taken quickly and easily from existing wells. Hydrogeologic studies and past water level measurements may be available to assist in interpretation of the data.

Existing wells may not be located in close enough proximity to the abandoned well or in great enough numbers to either detect the anomaly, determine if an anomaly exists or locate the abandoned well with any degree of certainty. This may necessitate the drilling of additional wells to monitor water levels or the use of another method to locate the abandoned well. Additionally, anomalous water-level readings may be caused by other sources and not enough hydrogeologic information may be available to provide adequate interpretation.

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SECTION 17

INJECTION

SYNOPSIS

Injection operations may cause abandoned wells to flow at the ground surface where no previous expression of the well was evident. This can occur when the pressure is sufficient, the top of the well is close enough to the surface and a direct conduit between the injection zone and the surface still exists. This method is not employed as a special technique to locate abandoned wells before issuance of a permit, but rather is a method of locating the well once injection operations have begun. The method is only applicable where injection operations cause an identifiable surface expression of the well and not when migration occurs without such an expression.

DISCUSSION AND PROCEDURES

Injection of fluid into an injection zone increases the pressure within the formation. The pressure may increase gradually if the formation is not filled with fluid or may be transmitted virtually instantaneously when the reservoir is already filled with fluid. Where the hydrostatic pressure or pressure created by injection exceeds the pressure within an overlying aquifer and a conduit exists between the two formations, fluid will migrate toward the formation with the lower pressure (refer to discussion in Section 16). If the pressure difference is great enough and if the abandoned well provides a direct connection to within a few feet of the surface, fluid may actually flow to the surface of the ground (EPA, 1977) (Figure 40). This surface expression of the abandoned well may then be identified. If, however, the casing has been removed, the hole has collapsed or the pressure is not sufficient, the fluid may not appear at the surface, but simply migrate into the formation below the surface (Figure 41).

The type of fluid that is injected into the formation may not necessarily be the fluid which first emanates at the surface. The injected fluid must physically be transmitted from the injection well through the formation and to the abandoned well before it can make its way to the surface. If the reservoir is not full of fluid at the time injection begins, the injected fluid must first fill the reservoir and push the original formation fluid away from the well. If the reservoir is full when injection begins, the pressure will be transmitted virtually instantaneously, very similarly to the water in a pressurized domestic

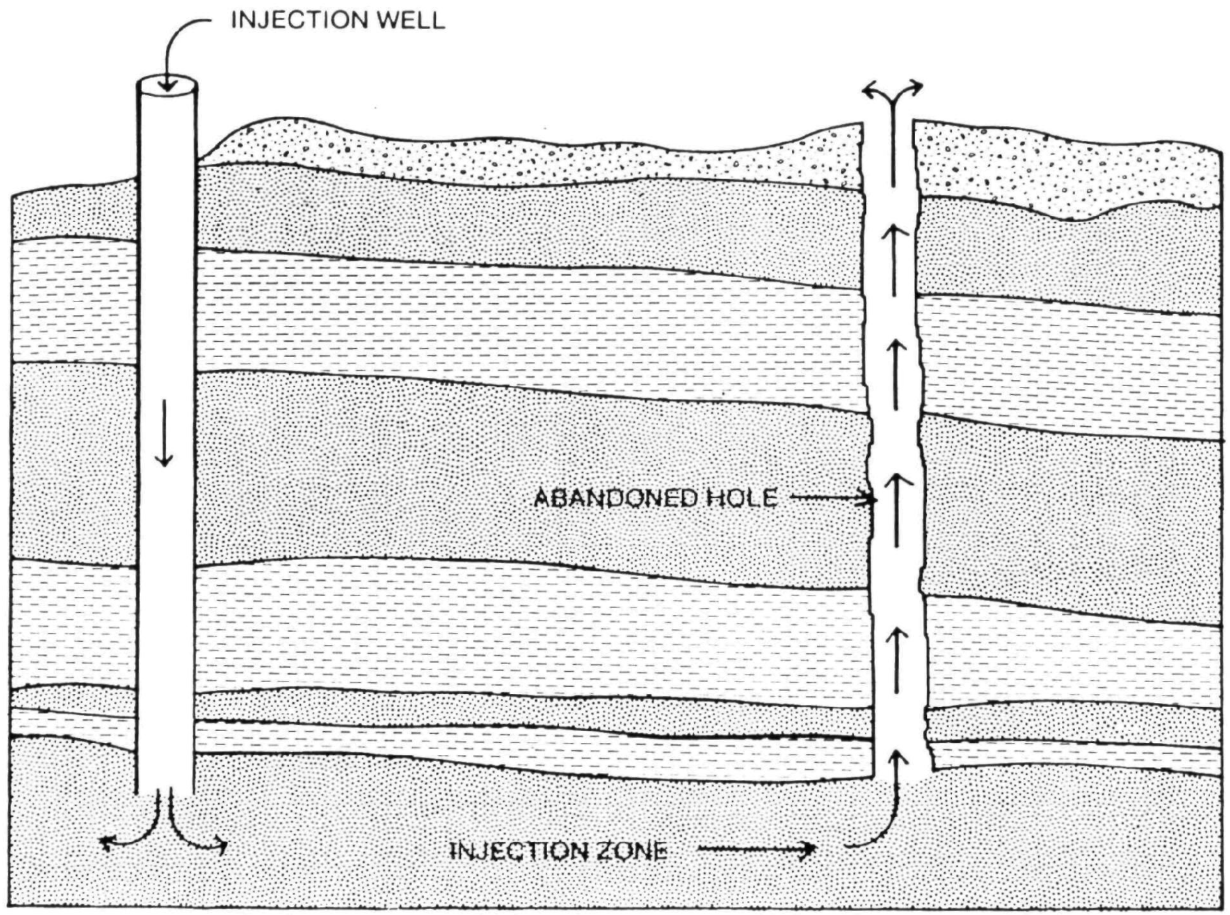

Figure 40. Diagram of the relationship between an injection well and a flowing abandoned well.

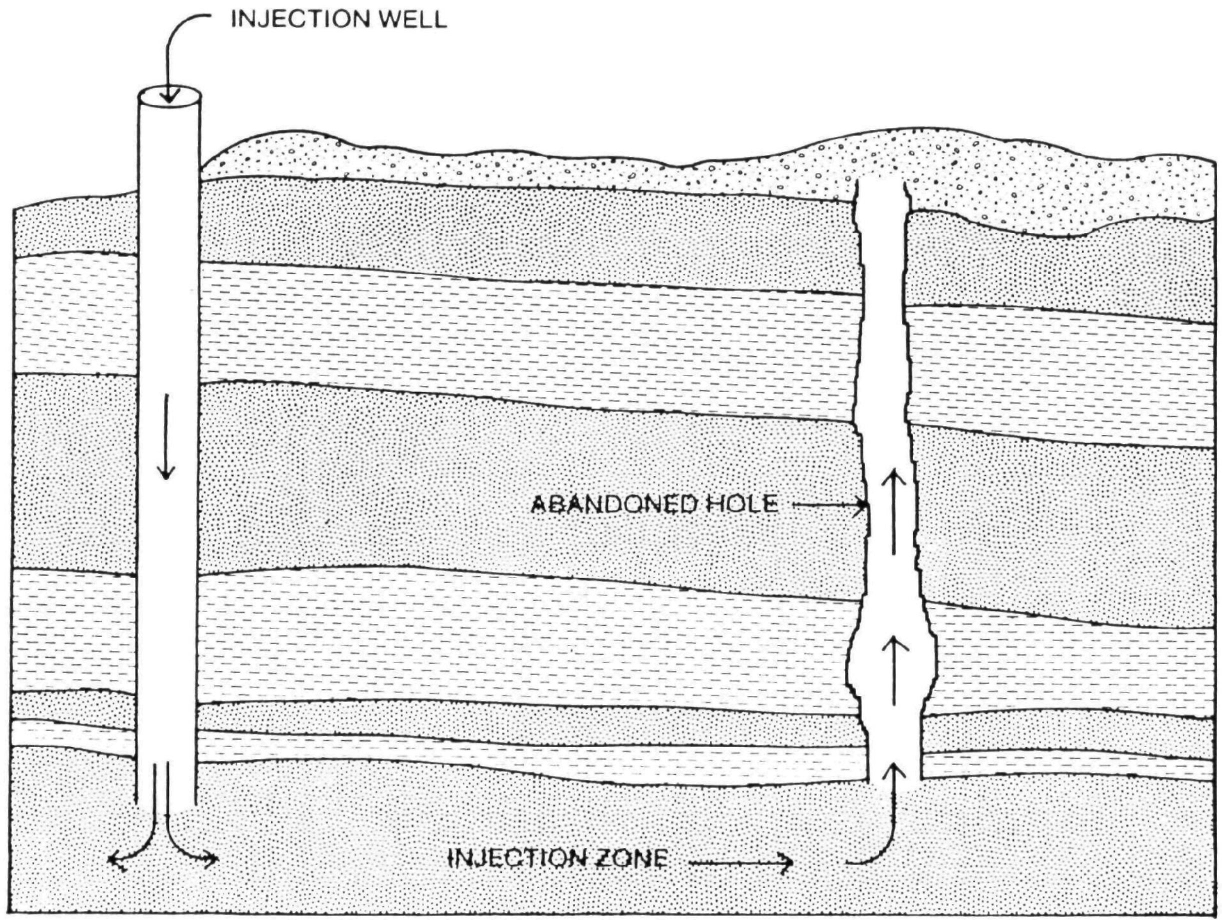

Figure 41. Diagram of the relationship between an injection well and an abandoned well which does not flow at the surface.

water line. The injection fluid can be likened to hot water which, even though the faucet is turned on and water is flowing, still takes a while to get to the outlet. This means that if test injection operations were conducted to specifically determine the presence of abandoned wells, even with a harmless fluid such as fresh water, the fluid within the formation would still migrate into the abandoned well before the fresh water. This could increase the potential for contamination to occur if sufficient quantities of formation fluid were forced into an aquifer or to the surface.

Injection operations are not normally executed specifically to determine the presence or location of abandoned wells. However, there may be situations where injection operations are in progress and a flowing hole appears either instantaneously or at a later date. When this occurs, the method has proven effective in locating the abandoned well and plugging operations should be conducted.

COST

There is no specific cost associated with locating abandoned wells by injection. Normally if an abandoned well begins to flow, the local property owner notifies someone as soon as it is discovered. This, in turn, usually prompts the need for plugging operations which can be quite expensive.

ADVANTAGES AND DISADVANTAGES

Injection operations may determine the location of an abandoned well when injection pressures are sufficient and the abandoned well is close enough to the surface to cause the well to flow at ground level. When this happens, a surface expression of the well is evident and no further search methods need be employed.

Abandoned wells may not be found by this method if the pressure is not sufficient, the channel is not well defined or if the top of the well is not located close enough to the surface. However, the pressure may still be sufficient to cause migration of fluid into an aquifer, thereby causing ground-water contamination. Another disadvantage to this method is that even when injection operations are begun, a well which may flow at the surface may not immediately be evident, but may take an undeterminible amount of time to make itself known.

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Appendix A. REGULATIONS, REQUIREMENTS AND METHODS USED BY STATE GOVERNMENT AGENCIES TO LOCATE ABANDONED WELLS

State	Does state regulate abandoned oil and gas wells? Y = yes N = no	Does any agency actively attempt to locate abandoned wells by any of these methods 1-search of records, 2-land survey, 3-visual/logical, 4-metal detectors, 5-methane detectors, 6-magnetics	Do agencies require companies to locate abandoned wells? If yes, by what methods?	Regardless of regulations or agency activities, are you aware of successful methods used to locate abandoned wells? If yes, by what methods?
Alabama	Y	1	1	1
Alaska	Y	No	No	No
Arizona	Y	3-requires surface monuments	No	4
Arkansas	Y	No	No	No
California	Y	1,2,3,4	No	1,3,4
Colorado	Y	No	No	1,2,4
Florida	Y	No	No	No
Georgia	Y	1,2,3	No	1,2,3
Idaho	Y	No	No	No
Illinois	Y	No	No	1,2,3,4,6
Indiana	Y	1,2,3	No	1,2,3,4
Iowa	Y	No	No	No
Kansas	Y	1,2,3,4	No	1,2,3,4
Kentucky	Y	1,2,3	No	1,2,3,4,5
Louisiana	Y	1	1	1,2,3
Maryland	Y	No	No	No
Michigan	Y	1,2,3,4	No	1,2,3 4
Mississippi	Y	No	No	No
Missouri	Y	No	No	No
Montana	Y	No	No	1,2,3,4
Nebraska	Y	No	No	1,2,4 6
Nevada	Y	1,3	No	1,3
New Mexico	Y	1,2,3,4,5	1	1,2,3,5-talk to landowners
New York	Y	1,2,3,4	No	1,2,3
North Carolina	Y	1,3	No	No
North Dakota	Y	1,3	1,2	1,2,3
Ohio	Y	1,3,4,5	No	1,2,3,4,5
Oklahoma	Y	1,2,3	1,2,3	1,2,3
Oregon	Y	No	No	1,2 3
Pennsylvania	Y	1,3,5	Coal co required to locate known wells	1,2,3,4,5 + thermal
South Dakota	Y	1,2,3	No	1,2,3
Tennessee	Y	No	1,2,3	1,2,3
Texas	Y	?	?	?
Utah	Y	1 3	No	1,3
Virginia	Y	1	1,3	1,2,3
Washington	Y	1,2,3 4,5	No	1,2,3,4,5
West Virginia	Y	Not routine	No	No
Wyoming	Y	1 2,3 + injection	1 2 3, + injection	1,2,3

(continued)

Appendix A (continued)

State	Does the state require all oil and gas well logs to be filed with one centralized agency? Y = yes N = no	Are all existing (known) wells located on centralized maps? Y = yes N = no	Are there wells in your state drilled before adequate regulations were enacted which are not on centralized maps? Y = yes N = no	Primacy by your state for UIC? Y = yes N = no A = applied
Alabama	Y	Y	N	Y
Alaska	Y	N	N	N
Arizona	Y	Y	N	Y
Arkansas	Y	Y	Y	A
California	Y	Y	Y	A
Colorado	Y	Y	Y	Y
Florida	Y	Y	Y	A
Georgia	Y	Y	Y	N
Idaho	Y	N	Y	Y
Illinois	Y	Y	Y	Y
Indiana	Y	Y	Y	N
Iowa	Y	Y	Y	?
Kansas	Y	Y	Y	Y
Kentucky	Y	N	Y	N
Louisiana	Y	Y	N	Y
Maryland	Y	Y	Y	Y
Michigan	Y	Y	Y	N
Mississippi	Y	N	N	A
Missouri	Y	Y	Y	A
Montana	Y	Y	Y	N
Nebraska	Y	Y	N	Y
Nevada	Y	Y	Y	N
New Mexico	Y	Y	Y	Y
New York	Y	N	Y	N
North Carolina	Y	Y	N	A
North Dakota	Y	Y	N	Y
Ohio	Y	Y	Y	Y
Oklahoma	Y	N	No maps	Y
Oregon	Y	Y	N	Y
Pennsylvania	Y	N	Y	N
South Dakota	Y	Y	Y	N
Tennessee	Y	Y	N	N
Texas	Y	Y	Y	Y
Utah	Y	N	No maps	Y
Virginia	Y	Y	N	N
Washington	Y	Y	Y	A
West Virginia	Y	Y	Y	Y
Wyoming	Y	Y	N	Y

APPENDIX B

DEPOSITORY OF OIL AND GAS WELL LOGS

State	Agency Name and Address
Alabama	State Oil & Gas Board of Alabama P.O. Drawer O University, Alabama 35486 (205) 349-2852
Alaska	Alaska Oil & Gas Conservation Commission 3001 Porcupine Drive Anchorage, Alaska 99501 (907) 279-1433
Arizona	Arizona Oil & Gas Conservation Commission 1645 W. Jefferson, Suite 420 Phoenix, Arizona 85007 (602) 255-5161
Arkansas	Arkansas Oil & Gas Commission 314 E. Oak Street El Dorado, Arkansas 71730 (501) 862-4965
California	California Division of Oil & Gas 1416 - 9th Street, Room 1310 Sacramento, California 95814 (916) 445-9686
Colorado	Colorado Oil & Gas Conservation Commission 1313 Sherman Street, Room 721 Denver, Colorado 80203 (303) 866-3531
Florida	Florida Department of Natural Resources Bureau of Geology 903 West Town Street Tallahassee, Florida 32304 (904) 488-8217

Georgia	Georgia Department of Natural Resources Geologic Survey 19 Martin Luther King Dr. Room 400 Atlanta, Georgia 30334 (404) 656-3214
Idaho	Idaho Oil & Gas Conservation Commission P.O. Box 670 Coeur d'Alene, Idaho 83814 (208) 664-2171
Illinois	Illinois Geological Survey 121 Natural Resources Building Urbana, Illinois 61801 (217) 344-1481
Indiana	Indiana Department of Natural Resources Division of Oil & Gas 911 State Office Building Indianapolis, Indiana 46220 (317) 232-4055
Iowa	Iowa Geological Survey 123 North Capitol Street Iowa City, Iowa 52242 (319) 338-1173
Kansas	Kansas Corporation Commission Oil & Gas Division 200 Colorado Derby Building Wichita, Kansas 67202 (316) 263-1042
Kentucky	Kentucky Geological Survey University of Kentucky Lexington, Kentucky 40506 (606) 258-5863
Louisiana	Louisiana Office of Conservation P.O. Box 44275 Baton Rouge, Louisiana 70804 (504) 342-5540
Maryland	Maryland Geological Survey The Rotunda 711 W. 40th Street, Suite 440 Baltimore, Maryland 21211 (301) 338-7110

APPENDIX B (Continued)

Utah	Utah State Division of Oil, Gas & Mining 4241 State Office Building Salt Lake City, Utah 84114 (801) 533-5771
Virginia	Virginia Division of Mines & Quarries 219 Wood Avenue Big Stone Gap, Virginia 24219 (703) 523-0335
Washington	Washington Department of Natural Resources Oil & Gas Conservation Committee PY-12 Olympia, Washington 98504 (206) 459-6372
West Virginia	West Virginia Department of Mines 1615 Washington Street East Charleston, West Virginia 25311 (304) 348-2055
Wyoming	Wyoming Oil & Gas Conservation Commission 123 South Durbin Street P.O. Box 2640 Casper, Wyoming 82602 (307) 234-7147